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VIRGINIA CONSERVATION COMMISSION

VIRGINIA GEOLOGICAL SURVEY

ARTHUR BEVAN, *State Geologist*

Bulletin 68

Chemical Character of Ground Water in the Coastal Plain of Virginia

By

D. J. CEDERSTROM

PREPARED IN COOPERATION WITH THE GEOLOGICAL SURVEY OF THE UNITED STATES DEPARTMENT OF THE INTERIOR

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FOREWORD

This report contains the results of certain phases of systematic ground-water investigations in the Coastal Plain region of Virginia, made during the period from September, 1937, to December, 1945. The manuscript and illustrations were submitted to the printer on February 12, 1946, during the administration of Dr. Arthur Bevan as State Geologist, for publication. Because of delays and difficulties beyond the control of the Virginia Geological Survey, this Bulletin was not published and delivered to us until the date indicated below.

On September 1, 1947, the undersigned was appointed State Geologist of Virginia to succeed Dr. Arthur Bevan who resigned on that date.

WILLIAM M. MCGILL,
State Geologist.

VIRGINIA GEOLOGICAL SURVEY,
Box 1428, University Station,
Charlottesville, Virginia,
February 15, 1951.

LETTER OF TRANSMITTAL

COMMONWEALTH OF VIRGINIA
VIRGINIA GEOLOGICAL SURVEY
UNIVERSITY OF VIRGINIA

CHARLOTTESVILLE, VA., February 12, 1946.

To the Virginia Conservation Commission:

GENTLEMEN:

I have the honor to transmit for publication as Bulletin 68 of the Virginia Geological Survey, a report on *Chemical Character of Ground Water in the Coastal Plain of Virginia,* by Mr. D. J. Cederstrom of the Federal Geological Survey.

The ground water in the Coastal Plain of Virginia occurs in several belts, each of which has distinctive characteristics. The author discusses the character of the ground water in each of these belts and gives numerous analyses of the waters. These facts should be very useful to industries, municipalities, and all others who need reliable, up-to-date information about the ground waters in this area of potentially abundant supplies.

The regional investigation of ground waters and of their geology in the Coastal Plain of Virginia is a cooperative project of the Virginia Geological Survey and the United States Geological Survey. Reports so far published on the results of this investigation include Bulletin 58, Circulars 1 and 3, and Reprint Series No. 6. A major report, Bulletin 63, contains detailed information on the Coastal Plain in southeastern Virginia.

Respectfully submitted,

ARTHUR BEVAN,
State Geologist.

Approved for publication:
Virginia Conservation Commission,
Richmond, Virginia, February 14, 1946.
R. A. GILLIAM, *Executive Secretary and Treasurer.*

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By D. J. Cederstrom*

ABSTRACT

The Coastal Plain province of Virginia consists of unconsolidated sediments of Cretaceous, Eocene, Miocene and Pleistocene age which dip gently seaward and thicken to more than 2,000 feet in the eastern part of the area. South of James River, Lower Cretaceous sands are the most prominent aquifers, but north of James River, where the Eocene sediments are thicker, most deep wells end in Eocene strata. A few reach Upper (?) Cretaceous deposits.

In the western part of the province, along the Fall Zone, water from deep wells is soft and has a low total mineralization. The water, as it moves eastward, gains in mineral content and becomes a hard calcium-bicarbonate water. Still farther to the east it is softened by base exchange and is a soft sodium-bicarbonate water. In the vicinity of Chesapeake Bay, this water is somewhat brackish and in places contains more than 1,000 parts per million of chloride.

Gain in bicarbonate east of the hard water belt is accounted for by chemical or biochemical breakdown of sulfate with liberation of carbon dioxide, which subsequently forms bicarbonate.

South of James River, soft bicarbonate water from the Lower Cretaceous sediments commonly contains from 4 to 6 parts per million of fluoride. North of James River, the Eocene and Paleocene (?) sediments characteristically yield water containing from 1 to 3 parts of fluoride.

The high chloride content in the eastern part of the area is considered to be due to incomplete flushing of the sea water with which the sediments were once saturated.

The Yorktown formation of Miocene age yields moderately hard or hard calcium-bicarbonate water, whereas water from the basal Miocene Calvert and the Eocene Nanjemoy formations is soft to moderately hard and is more similar to water from older deposits.

*Associate Geologist, Geological Survey, U. S. Dept of the Interior.

Water from Columbia deposits of Pleistocene age is low in mineral content except where contaminated by salt spray or polluted.

Tables of analyses of each of the types of water discussed are given. The numbers given in references to Tables in the text refer to analyses given in the respective Tables.

INTRODUCTION

The present report is based upon localized and systematic studies by the writer as part of the cooperative investigations of ground-water resources of Virginia by the Virginia and Federal geological surveys. Some of the chemical analyses upon which this report is based were made as part of earlier investigations. [1, 10, 18*] Particular mention should be made of the investigation in 1918, of the geology and ground-water resources of the counties bordering Chesapeake Bay on the west and south, by Willis T. Lee, R. D. Mesler, W. C. Mansfield and A. G. Maddren, all of the U. S. Geological Survey. These data were not published, but analyses of water samples[16] which were collected have been most valuable.

A comprehensive report on the Coastal Plain counties in Virginia south of James River[6] has been published. A compilation of logs of deep wells in the area north of James River[5] and papers dealing with specific phases of Virginia Coastal Plain hydrology and geology have also been published,[3, 4, 7] but detailed reports on a large part of the Coastal Plain will not be published in the near future. In the present report, therefore, the broader aspects of the geology of the Virginia Coastal Plain, including recently acquired data, are summarized, in addition to the discussion of the chemical character of ground waters of the entire Virginia Coastal Plain. A relatively large number of analyses, most of them unpublished, is given in order that data on the chemical quality of ground water throughout the Coastal Plain may be made available, pending the publication of detailed reports.

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*Numbers refer to publications listed at end of this report.

OUTLINE OF GEOLOGY

The Coastal Plain province of Virginia is underlain by unconsolidated clays, sands and marls which dip gently seaward (Fig. 2). Westward these sediments thin to a feather edge along the Fall Zone, which extends approximately north-south in Virginia and passes through Emporia, Petersburg, Richmond, Fredericksburg and Washington, D. C.[8] The Fall Zone is the frayed western margin of the blanket of Coastal Plain sediments. There the granitic rock basement is close to the surface and, in places where the thin cover of sediments has been removed by erosion, the rock is exposed. East of the Fall Zone, basement rock lies at progressively greater depths and the unconsolidated sediments thicken to more than 2,000 feet, as at Norfolk and Mathews. The sediments of the Coastal Plain extend eastward from the shore to the edge of the Continental Shelf, where they may be about 12,000 feet thick.[13]

Alternating sands, clays and sandy clays of the Potomac group (Lower Cretaceous) rest upon the granitic bedrock. This group of sediments is nonmarine in origin. The sands included in the group are prolific aquifers and, where favorable thicknesses are present, yield millions of gallons of water a day to wells. Above the Potomac group of sediments, alternating sands and clays of the Upper Cretaceous are present. These sediments do not extend westward to the Fall Zone. In southeastern Virginia, Upper Cretaceous mottled clays of a nonmarine aspect, probably shore-line deposits, extend inland at least as far as Southampton County.[15] North of James River mottled clays underlying the Eocene beds are tentatively assigned to the Paleocene*.[15] These deposits contain excellent water-bearing formations in places.

The outcropping Pamunkey group of sediments consists of the Aquia formation[9] (lower Eocene) and the Nanjemoy formation (lower and middle Eocene), which have been described in the literature.

The Nanjemoy formation has recently been recognized in cuttings from many deep wells east of the Fall Zone. It is a good water-bearing formation in places.

Above the older Eocene deposits lies the Upper Eocene Chickahominy formation.[9a] It is 80 feet thick at Yorktown. To date these deposits are known to be present[5] at Drivers in Nansemond County, Norfolk and Newport News, Yorktown and Camp Peary in York County, and Byrdton in Northumberland County.

*Cushman, J. A., Personal communications, Sept. 28, 1944, and June 10, 1947.

The Eocene deposits are marine sediments which consist largely of clayey glauconitic beds and subordinate sand and thin limestone members. The clayey strata range in color from dull-gray, blue and brown to brilliant green. The uppermost Eocene beds (Jackson group) are not known to contain sandy members.

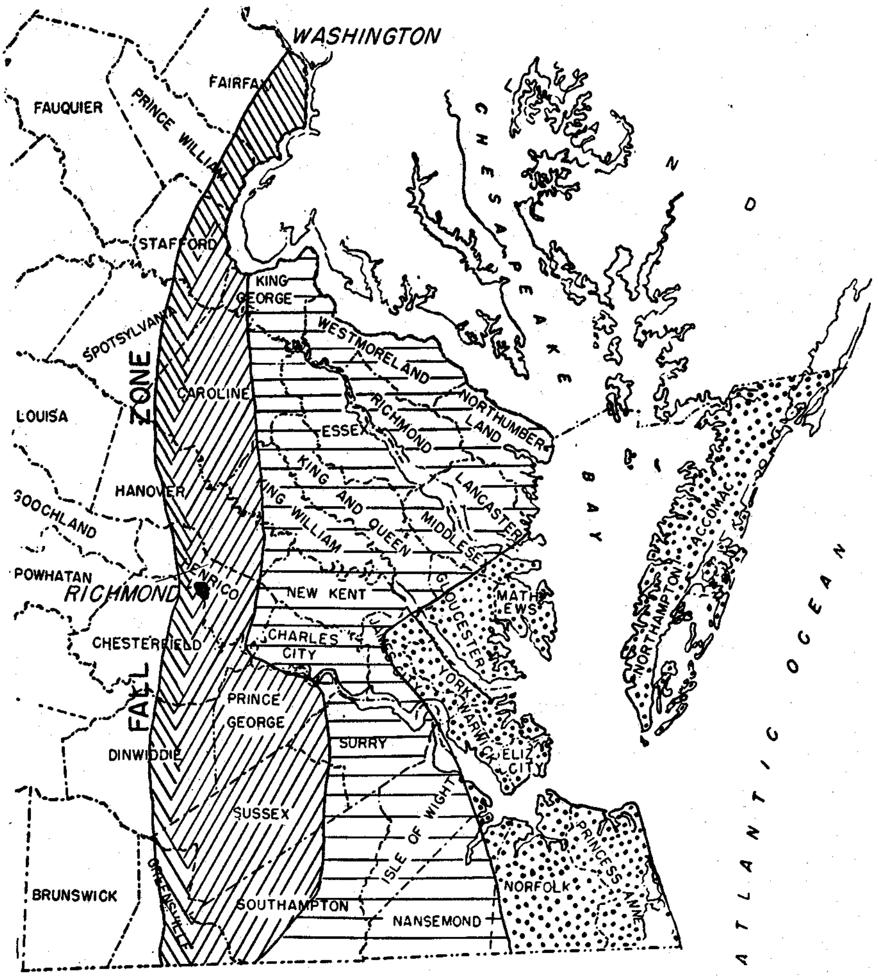
North of James River the Eocene deposits thicken somewhat and extend to greater depths than in the area to the south.[4] As a result, many deep wells north of James River end in Eocene deposits, in contrast to those of the south which everywhere tap Cretaceous deposits. Although they furnish excellent yields to wells in many places, the Eocene sands seem to be very variable in thickness and permeability. The deeper Paleocene (?) sands are thicker and more dependable as a source of supply and have been extensively developed at West Point and in the Northern Neck section of Virginia.

The Chesapeake group (Miocene) of marine marls and subordinate sandy formations overlies the Pamunkey group of sediments. The basal Calvert (?) formation yields small to moderate supplies of water in a few counties. Water from this horizon is similar to water from the underlying Eocene sediments. Relatively shallow wells obtain generally not more than 100 gallons a minute from the sandy Yorktown formation of the Chesapeake group, particularly in the area bordering Chesapeake Bay. This water is distinctly different from that produced from deeper wells reaching basal Miocene beds. Although under slight artesian head, wells penetrating the Yorktown formation are not generally spoken of as "artesian".

The entire Coastal Plain province is veneered by the Columbia group of terrace sands and clays (Pleistocene). The sediments on the higher terraces are continental in origin, whereas those on the lower easterly terraces are marine.[2] Thousands of shallow dug or driven wells generally obtain small supplies of water from the terrace sediments throughout the Coastal Plain.

The Coastal Plain sediments dip seaward at a rate of about 10 feet per mile. The seaward slope is not uniform, however, and locally strata dip to the south or north.

The area under consideration is shown in Figure 1.



Belt of soft water of low mineralization

Belt of soft sodium-bicarbonate water

Belt of hard bicarbonate water

Belt of high-chloride water

FIGURE 1.—Map of eastern Virginia showing geographic distribution of the major types of artesian waters.

BELTS OF ARTESIAN WATER

For the purpose of this Bulletin the Coastal Plain province is divided into several belts, based on the differences in chemical character of the waters yielded by deep wells penetrating the sands of Cretaceous, Paleocene (?) and Eocene age which are the most important water-bearing strata in the province, and, to a lesser extent, upon the differences in the geology of these strata. These divisions are: the Fall Zone belt, the adjacent belt of hard bicarbonate waters, the central belt of soft bicarbonate waters, and the eastern belt of high-chloride waters (Fig. 1).

Along the Fall Zone, water from the deep wells is generally soft and has a low total mineralization. As the water moves eastward it gains in mineral content, mostly as calcium bicarbonate, and becomes hard, but still farther to the east it is softened by base exchange and becomes a soft sodium-bicarbonate water. In the vicinity of Chesapeake Bay, the sodium-bicarbonate water is somewhat brackish due to the presence of small amounts of connate water, and in places it contains more than 1,000 parts per million of chloride.

BELT OF SOFT WATER OF LOW MINERALIZATION

The Fall Zone, that area where the thin western fringe of the blanket of Coastal Plain sediments lies upon but does not wholly cover the granitic bedrock, is a rather poor ground-water zone both as to the quality and the quantity of water available. Only a relatively few wells obtain water from Coastal Plain sands along the Fall Zone, and the water yielded is low in total mineral content. About 100 parts per million total dissolved solids may be considered the average (Table A, 3, 8, 9). In places the water contains objectionable amounts of iron (analyses 8, 9) and is corrosive due to dissolved free carbon dioxide (analysis 4). It may be noted that the fluoride content of water from sands of the Potomac group along the Fall Zone is everywhere less than 1 part per million.

Analyses of several samples of water, from wells which penetrate granitic rock along the Fall Zone, show a rather wide range of mineralization. One well at Petersburg (Table A, 6) contains 232 parts per million total dissolved solids, but a well at Chester (Table A, 2) yields water containing 857 parts. Most of the waters from granitic rock are hard; the hardness may be present

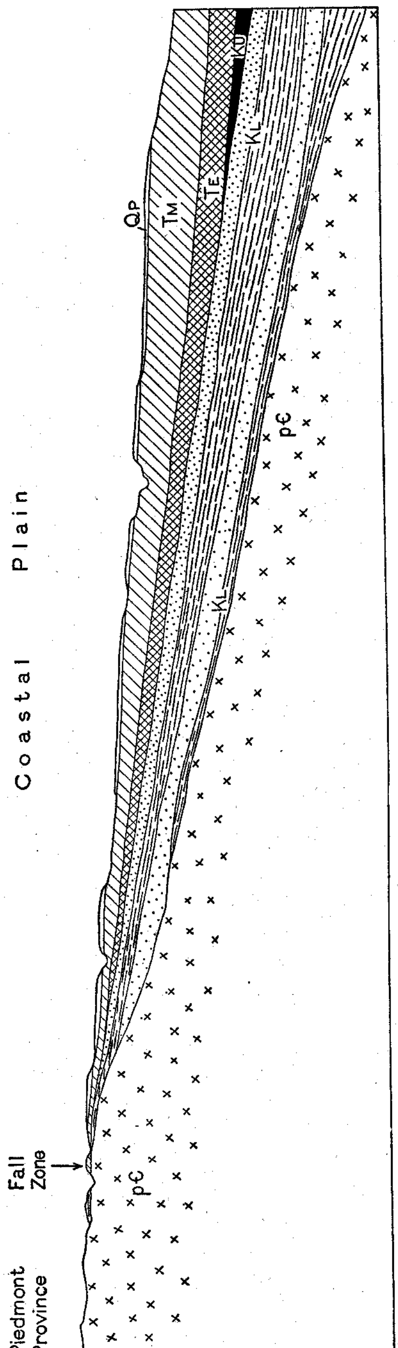


FIGURE 2.—Generalized section of the Virginia Coastal Plain. QP, Pleistocene terrace formations (Columbia group); TM, Miocene marl (Chesapeake group); TE, Eocene glauconitic sand and marl (Pamunkey group); KU, Upper Cretaceous sands and clays; KL, Lower Cretaceous sands and clays (Potomac group); pЄ, Crystalline basement rock, chiefly pre-Cambrian. From Geological Survey Bulletin 58, by D. J. Cederstrom.

either as non-carbonate or carbonate hardness. In some places iron is present in troublesome quantities.

It is of particular interest to note that some waters derived from granitic rock have a high fluoride content, 3.4 and 7.7 parts per million being noted in Table A, 2 and 5. In one well the fluoride occurs in a hard calcium-sulfate water; in the other, in a soft sodium-bicarbonate water. The presence of fluoride in water from wells penetrating granitic rock suggests that the high fluoride content of the soft sodium-bicarbonate waters to the east is derived from some mineral in the sediments which was derived from granites of the Piedmont region, rather than that the source is a chemically precipitated mineral, such as glauconite.

BELT OF HARD BICARBONATE WATERS

Immediately east of the Fall Zone is a belt in which wells penetrating artesian strata yield a hard bicarbonate water (Figs. 1 and 7). The belt has a maximum width of 25 miles south of James River, but north of Fredericksburg the hard water belt seemingly thins to a vanishing point.

Hardness.—The water has a variable amount of hardness, generally as calcium and magnesium bicarbonate; the total hardness was found to be less than 190 parts per million (Table B, 2, 7, 14, 17) with one exception; one sample (Table B, 4) from King George County has 270 parts of total hardness.

Sulfate (noncarbonate) hardness is present in the sample from King George County (Table B, 4), but in samples 1, 7, and 11, containing rather high sulfate for this zone, respectively 25, 36, and 75 parts per million, there is no noncarbonate hardness. Sulfate is generally less than 16 parts per million, but, as noted above, the sulfate occasionally may be much higher.

Bicarbonate and carbon dioxide.—Water falling to the earth as rain and percolating through the soil cover into the zone of saturation along the Fall Zone, takes a variable amount of carbon dioxide into solution. As the water moves eastward in the sediments, the carbon dioxide reacts with calcareous material and the hardness increases until the free carbon dioxide is consumed. When the amount of free carbon dioxide, which is found in several samples along or east of the Fall Zone, is converted to bicarbonate hardness* and is added to the hardness already pres-

*CO_2 in parts per million multiplied by 2.27 equals hardness as $CaCO_3$.

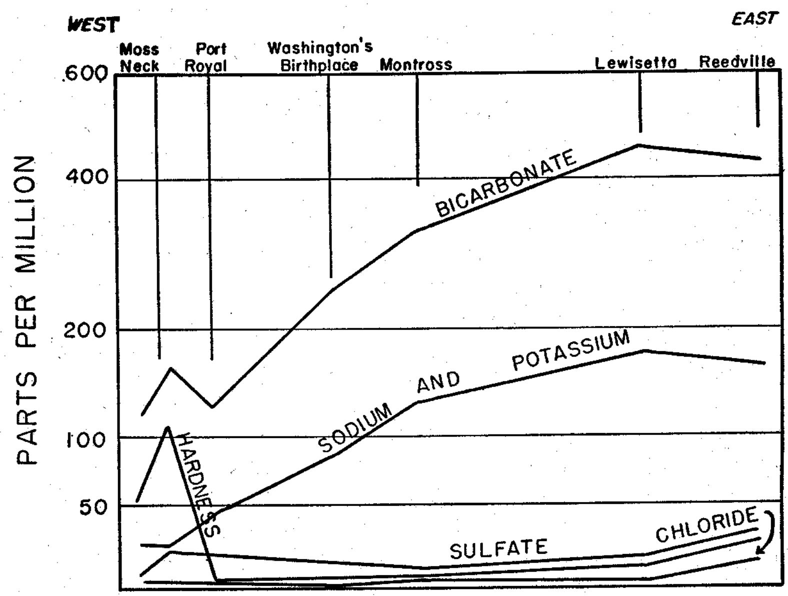


FIGURE 3.—Graph showing down-dip increase in mineral content of artesian waters from Moss Neck, Caroline County, to Reedville, Northumberland County, Virginia.

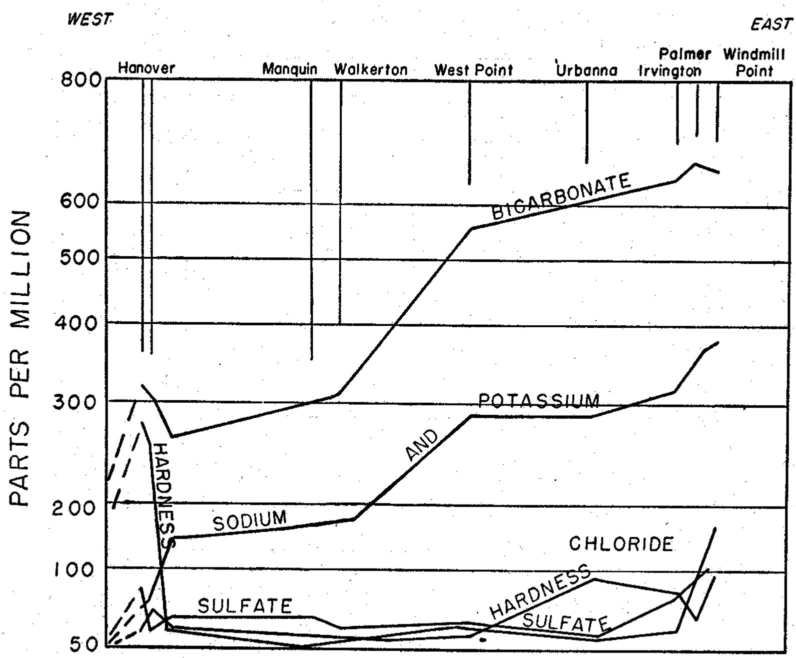


Figure 4.—Graph showing down-dip increase in mineral content of artesian waters from Hanover, Hanover County, to Windmill Point, Lancaster County, Virginia.

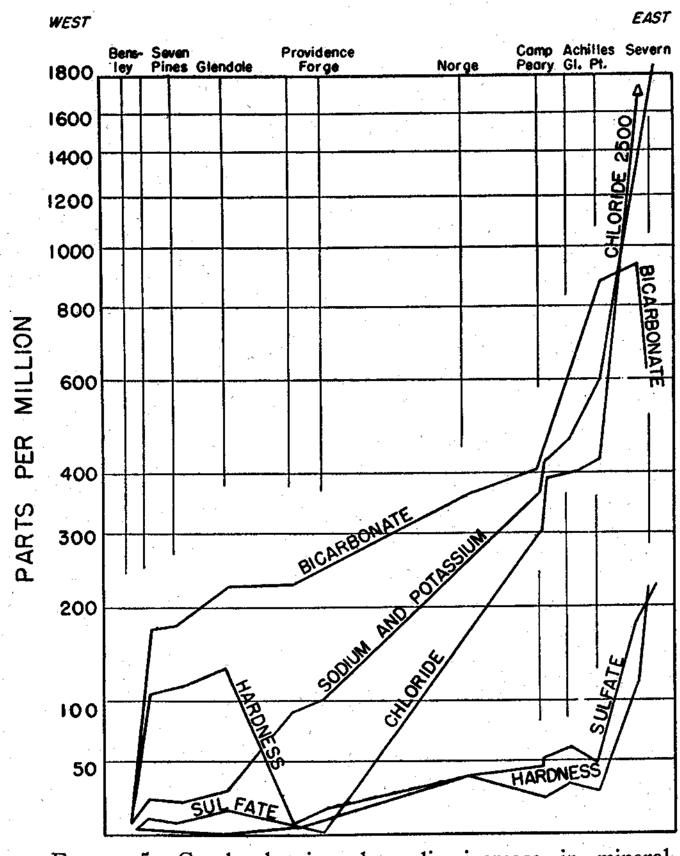


FIGURE 5.—Graph showing down-dip increase in mineral content of artesian waters from Bensley, Chesterfield County, to Severn, Gloucester County, Virginia.

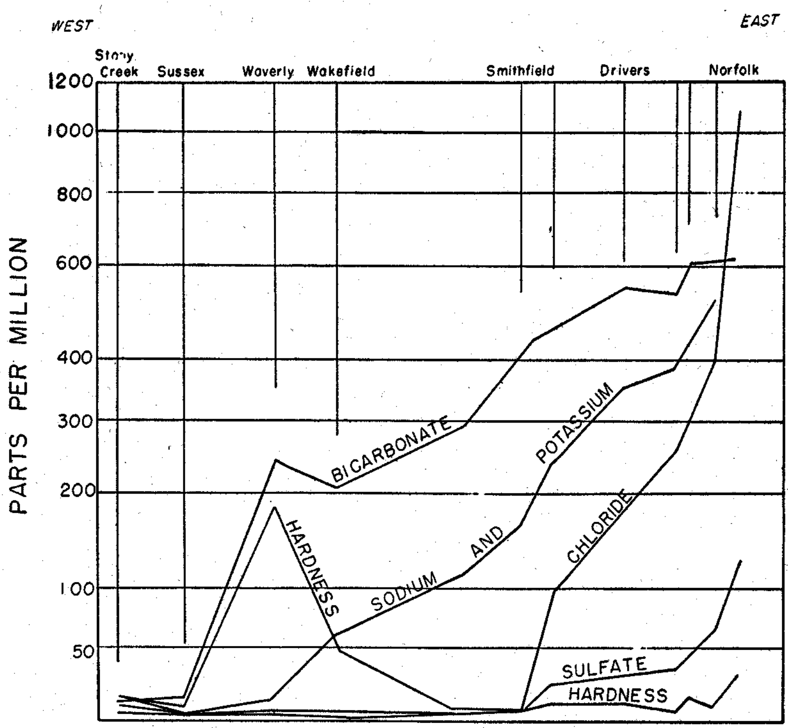


FIGURE 6.—Graph showing down-dip increase in mineral content of artesian waters from Stony Creek, Sussex County, to Norfolk, Norfolk County, Virginia.

TABLE A.—*Analyses of ground waters from wells along the Fall Zone*
(Parts per million)

Well No.	1	2	3	4	5
County	Caroline	Chesterfield	Chesterfield	Chesterfield	Dinwiddie
Town	Ruther Glen	Chester	Chester	Bensley	Petersburg
Depth (feet)	151	372	152	63	700
Water-bearing rocks	Pre-Cambrian	Pre-Cambrian	Pre-Cambrian	Pre-Cambrian	Pre-Cambrian
Silica (SiO_2)	...	17	52	...	...
Iron (Fe)	...	.03	.40	...	...
Calcium (Ca)	...	67	17	...	...
Magnesium (Mg)	...	5.0	7.0	...	...
Sodium (Na)	...	197	6.1	...	...
Potassium (K)	...	14	3.7	...	...
Bicarbonate (HCO_3)	146	126	93	4.0	292
Sulfate (SO_4)	10	468	8.8	2	15
Chloride (Cl)	1	24	2.1	6	23
Fluoride (F)	.0	3.4	.4	.0	7.7
Nitrate (NO_3)	.0	.10	...	9.4	0
Free carbon dioxide (CO_2)	1.4	5.0	8.3	44	...
Total dissolved solids	...	857	138	...	...
Total hardness (as $CaCO_3$)	99	188	71	15.0	15
Analyst[a]	EWL	MDF	MDF	DMD	MDF
Date of collection	Dec. 31, 1943	Nov. 8, 1939	Nov. 8, 1939	May 17, 1944	Apr. 3, 1941

[a] EWL = E. W. Lohr, MDF = M. D. Foster, DMD = D. M. Derrick.

TABLE A.—*Analyses of ground waters from wells along the Fall Zone—Continued*
(Parts per million)

Well No.	6	7	8	9	10
County	Dinwiddie	Dinwiddie	Sussex	Greensville	King George
Town	Petersburg	Carson	Stony Creek	Jarratt	Tylertown
Depth (feet)	170	118	38	98	456
Water-bearing rocks	Pre-Cambrian	Pre-Cambrian	Lower Cretaceous (?)	Lower Cretaceous (?)	Pre-Cambrian
Silica (SiO_2)	41	....	39	30	....
Iron (Fe)	.65	....	4.31	8.9	4.2
Calcium (Ca)	40	....	3.2	8.4	....
Magnesium (Mg)	7.3	....	2.0	2.7	....
Sodium (Na)	25	....	8.7	9.8	....
Potassium (K)	6.1	....	.3	14	....
Bicarbonate (HCO_3)	214	101	12	60	64
Sulfate (SO_4)	7.6	5	4.9	9.6	85
Chloride (Cl)	2.6	3	14	8.1	755
Fluoride (F)	.3	.2	.0	.0	.1
Nitrate (NO_3)	.33	.0	.05	.98	....
Free carbon dioxide (CO_2)	2.5	....	....	....	....
Total dissolved solids	232	....	85	120	....
Total hardness (as $CaCO_3$)	130	78	16	32	758
Analyst[a]	MDF	MDF	MDF	MDF	EWL
Date of collection	July 13, 1939	June 10, 1939	Nov. 27, 1937	Apr. 19, 1938	Sept. 15, 1944

[a] MDF = M. D. Foster, EWL = E. W. Lohr.

TABLE B.—*Analyses of ground waters from wells in the belt of hard bicarbonate waters*
(Parts per million)

Well No.	1	2	3	4	5	6	7
County	Stafford	Stafford	Spotsylvania	King George	Caroline	Caroline	Hanover
Town	Widewater	Fredericksburg	Port Royal Forks	Fairview Beach	Bowling Green	Moss Neck	Hanover
Depth (feet)	290	195	300	105	312	160	129
Water-bearing rocks	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous	Eocene	Lower Cretaceous	Eocene	Lower Cretaceous
Silica (SiO_2)	......	......	......	......	......	......	......
Iron (Fe)	2.6	13	......	......	......	......	.20
Calcium (Ca)	......	......	......	......	......	......	......
Magnesium (Mg)	......	......	......	......	......	......	......
Sodium (Na)	......	......	......	......	......	......	......
Potassium (K)	......	......	......	......	......	......	......
Bicarbonate (HCO_3)	56	79	116	246	82	164	220
Sulfate (SO_4)	25	17	8	85	1	21	36
Chloride (Cl)	2	3	5	6	9	3	9
Fluoride (F)	......	.3	.2	.2	0	0	.2
Nitrate (NO_3)	.0	0	.4	1.0	22	.4	.9
Free carbon dioxide (CO_2)	33	35	16	1.4	32	12	.7
Total dissolved solids	......	......	......	......	......	......	......
Total hardness (as $CaCO_3$)	72	74	51	270	39	114	180
Analyst[a]	MDF	EWL	DMD	DMD	EWL	DMD	EWL
Date of collection	Apr. 26, 1940	Jan. 1, 1944	Apr. 1, 1944	Apr. 2, 1944	Dec. 28, 1943	Apr. 1, 1944	Dec. 31, 1943

[a] MDF = M. D. Foster, EWL = E. W. Lohr, DMD = D. M. Derrick.

TABLE B.—*Analyses of ground waters from wells in the belt of hard bicarbonate waters—Continued*
(Parts per million)

Well No	8	9	10	11	12	13	14
County	Hanover	Henrico	Henrico	Henrico	Henrico	Henrico	Prince George
Town	Hanover	San Rafael	Highland Springs	Robinwood	Sandston	Glendale	Prince George
Depth (feet)	154	181	270	196	272	232	129
Water-bearing rocks	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous	Eocene	Lower Cretaceous
Silica (SiO_2)	8.0	26	...	...	44	27	26
Iron (Fe)	2.6	.03	...	1.7	.03	1.6	2.37
Calcium (Ca)	41	26	...	...	29	32	69
Magnesium (Mg)	12	11	...	...	10	13	3.1
Sodium (Na)	28[a]	24	...	...	22	29	3.7
Potassium (K)							2.0
Bicarbonate (HCO_3)	210	177	151	204	183	226	225
Sulfate (SO_4)	7.7	13	12	75	7.9	6.7	6.0
Chloride (Cl)	23	2.1	2	69	2.4	2.2	2.2
Fluoride (F)	.1	0	.3	1.9	.0	.3	.0
Nitrate (NO_3)	.0	0	.1	.4	.1	.0	.0
Free carbon dioxide (CO_2)	.0	.4	4.0	7.6	4.0	1.1	.0
Total dissolved solids	224	183	...	...	200	224	225
Total hardness (as $CaCO_3$)	152	110	24	34	114	133	185
Analyst[b]	EWL	EWL	EWL	EWL	EWL	EWL	MDF
Date of collection	Dec. 31, 1943	Dec. 30, 1943	Dec. 30, 1943	Dec. 30, 1943	Dec. 30, 1943	Dec. 29, 1943	July 14, 1939

[a] Calculated.
[b] EWL = E. W. Lohr, MDF = M. D. Foster.

TABLE B.—*Analyses of ground waters from wells in the belt of hard bicarbonate waters*—*Continued*

(Parts per million)

Well No.	15	16	17	18	19	20	21
County	Prince George	Prince George	Sussex	Sussex	Sussex	Southampton	Southampton
Town	Hopewell	Burrowsville	Waverly	Wakefield	Gray	Little Texas	Capron
Depth (feet)	60	120	240	235	97	190	265
Water-bearing rocks	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous
Silica (SiO_2)	...	31	37	18	...	...	...
Iron (Fe)	5.14	.25	.03	.08	...	1.27	...
Calcium (Ca)	...	38	58	12	...	...	...
Magnesium (Mg)	...	10	10	4.8	...	...	...
Sodium (Na)	...	15	14	61	...	...	...
Potassium (K)	...	19					
Bicarbonate (HCO_3)	75	222	244	210	244	187	200
Sulfate (SO_4)	10	3.3	6.0	3.0	1	12	18
Chloride (Cl)	3	3.0	2.9	2.2	3	4	2.0
Fluoride (F)	.4	.4	.2	.0	0	0	0
Nitrate (NO_3)	.0	1.1	2.0	1.9	0	.13	.41
Free carbon dioxide (CO_2)	23	2.2	...	...	.7	...	...
Total dissolved solids	...	219	245	209	...	...	...
Total hardness (as $CaCO_3$)	62	136	186	50	162	136	146
Analyst[a]	MDF	MDF	MDF	MDF	MDF	WMN	MDF
Date of collection	July 7, 1939	Oct. 3, 1939	Nov. 26, 1937	Nov. 26, 1937	Nov. 10, 1938	Sept. 22, 1937	Sept. 14, 1937

[a] MDF = M. D. Foster, WMN = W. M. Noble.

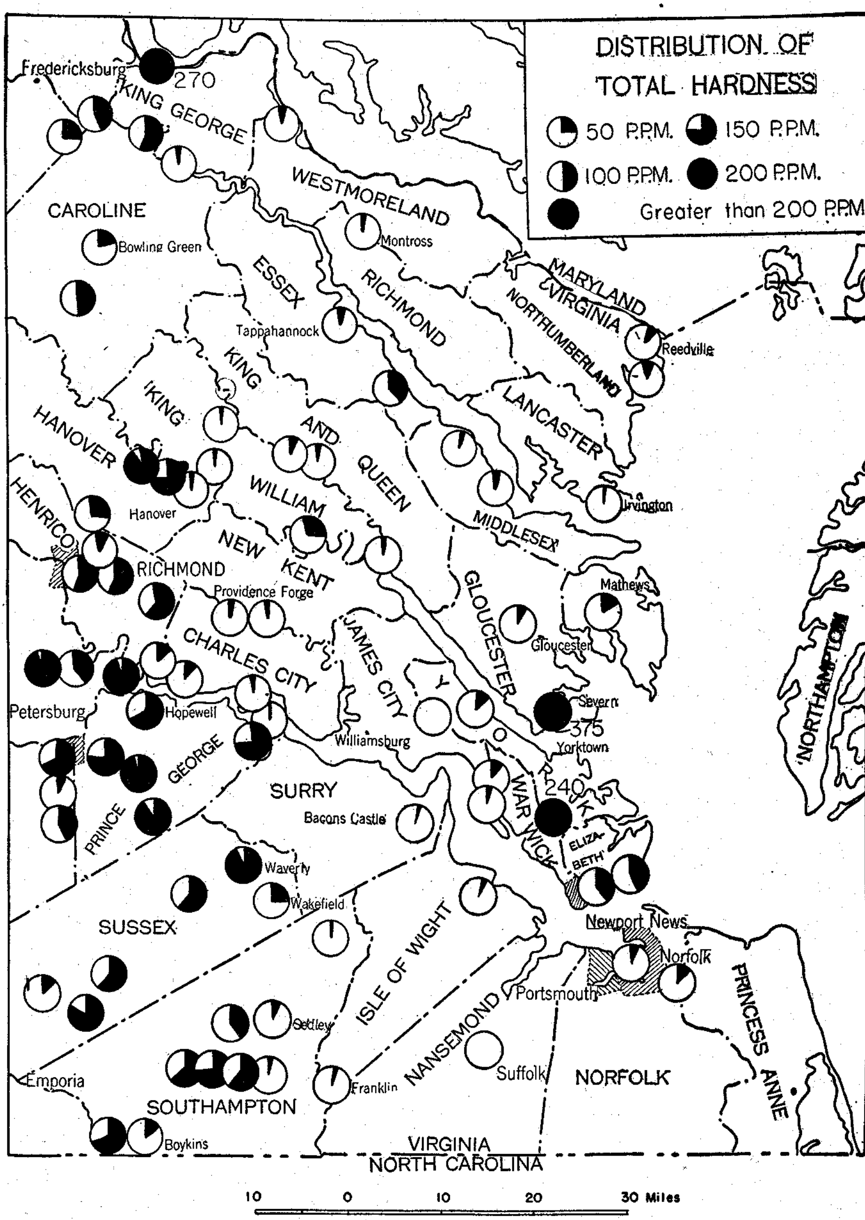


FIGURE 7.—Map showing distribution of total hardness in artesian waters in eastern Virginia.

ent, it is indicated that from 100 to 150 parts per million of total hardness may originate by this means (Table A, 4; Table B, 2, 6). This calculated maximum hardness is slightly lower than the maximum found in the belt of hard waters (Figs. 3-6 and Table B).

Free carbon dioxide is fairly high in the western part of the hard water belt (Table B, 1, 5, 15), but in the eastern portion of the belt it may be less than two parts per million (Table B, 4, 7, 9, 13, 19).

Base exchange.—At a variable distance from the Fall Zone, the hard waters are softened by base exchange; hence, beyond a certain point, the hard waters decrease in calcium and magnesium and gain in sodium. Essentially no other change in mineral content occurs.

The loading of sediments with exchangeable sodium may have occurred in Miocene time. The Miocene strata are of marine origin, and certainly when these deposits were formed, all the older Coastal Plain sediments were thoroughly saturated with sea water and loaded with exchangeable sodium up to the present Fall Zone. However, even if Pleistocene terraces up to a height of only 100 feet above sea level are considered to be of marine origin[2] it is likely that at the highest stand of the Pleistocene seas leakage into Coastal Plain sediments occurred at points of low altitude along the Fall Zone, as in the Petersburg-Richmond area. The areas of high ground between Fredericksburg and Richmond and south of Petersburg and the outcrop area would not be flooded by a 100-foot sea and, in fact, hydrostatic head there would be sufficient to keep the salt-water contact there many miles to the east. Viewed areally, the salt-water contact of the artesian system should then be sinuous, trending west where major streams cross the Fall Zone at low altitudes and trending east in the higher interstream areas. The suggestion may be offered that the hard water-soft water contact, which trends sharply eastward south of James River, may reflect an incomplete saturation of Coastal Plain strata by sea water resulting from a 100-foot stand of the sea. If the hard water-soft water contact trended eastward similarly north of Richmond, the suggestion would be more plausible, but the contact does not appear to do so. The apparent thinning or absence of the hard water belt from Quantico to Alexandria suggests that there the Coastal Plain sediments were lately flooded by sea water and loaded with sodium to the Fall Zone, in consequence of deep dissection and low hydrostatic head along the north-south course of Potomac River.

An alternative explanation is that sodium clays originally extended to the Fall Zone everywhere but have been differentially converted to calcium (and magnesium) clays because of differences in volume of the eastward flow of hard waters arising from differences in artesian head, and permeability and thicknesses of water-bearing sands.

In moving down dip from the Fall Zone, artesian waters tend to gain in calcium bicarbonate until all the free carbon dioxide is exhausted. However, base exchange begins to be effective immediately east of the Fall Zone, even though the water is gaining greatly in calcium, and, as a result, high calcium samples (Table B) generally contain a little sodium bicarbonate, generally about 20 to 30 parts per million. They do not contain more because the sediments are in large part loaded with exchangeable calcium. The system has progressed towards an almost complete calcium loading of the exchangeable clays as far east as free carbon dioxide persists in the waters.

At Highland Springs and Robinwood (Table B, 10, 11), about 50 and 160 parts of sodium are present, respectively. Both of these samples have a low hardness, and apparently more softening has taken place locally than in most places in this belt. The sample from Robinwood is also unusual in having a rather high chloride content, 69 parts per million. This may be due to incomplete flushing of connate water with which the sediments were once saturated.

It may be expected that, in this artesian system, the eastern front of the hard water belt will retreat eastward from the points at which free carbon dioxide is entirely consumed, and in the eastern part of the hard water belt there should be a narrow zone where calcium is exchanged for sodium but no gain in bicarbonate occurs. This zone of no gain in bicarbonate exists and is clearly shown on the graphs (Figs. 3-6). In eight places, where samples are available across the eastern portion of the hard water belt, this relationship is found to be true.

In the zone of no gain in bicarbonate, referred to above, there is apparently loss of bicarbonate in an easterly direction in some places (Figs. 3, 4 and 6). This apparent "loss" is considered to be due to sampling across instead of along the lines of flow of ground water. For instance, hard water at Burrowsville in Prince

George County (Table B, 16), contains almost exactly as much bicarbonate as the soft water at Brandon to the northeast because in the Burrowsville area the flow is in a northeasterly direction towards James River flowing well field. In northern Sussex County (Figs. 6 and 7) the sample from Wakefield, containing a lower bicarbonate than the samples from Waverly to the northwest, is water which has by-passed Waverly and moved in from the west or southwest. Slight gains in bicarbonate immediately after the sharp initial gain (Fig. 5) are similarly explained. Small discrepancies may in fewer instances be attributed to the impossibility of everywhere sampling from the same horizon. By and large, however, an area of no gain in bicarbonate seems to be characteristic, and deviations from the norm seem susceptible to the explanation given above.

BELT OF SOFT SODIUM-BICARBONATE WATERS

East of the belt of hard water, the water obtained from artesian strata is a soft sodium-bicarbonate water (Table C). As such, the belt extends to the sea but, in the Chesapeake Bay area, water of this type contains an admixture of connate water and is discussed separately. The belt of low-chloride sodium-bicarbonate water extends as far east as a line drawn southwestward from the tip of Lancaster County to Toano in James City County and thence southeastward through northern Nansemond County (Fig. 1). The belt includes most of the northern part of the Virginia Coastal Plain but narrows to a strip 25 miles wide in the upper York-James Peninsula. South of James River, the zone is from 25 to 35 miles wide.

Bicarbonate content.—The bicarbonate content of water in the sodium-bicarbonate zone increases progressively eastward, as shown in Figures 3-6. It ranges from about 125 to 250 parts per million on the western boundary of the zone and increases to 400 to 800 parts per million in the eastern portion of the zone.

The bicarbonate content is of importance, since this constituent contributes to the foaming tendencies of the water when used in boilers. Tolerance varies with the temperature and pressures used; in some instances a rather high bicarbonate water (628 parts per million, at Suffolk) can be used in low pressure boilers if frequently "blown down" to remove excess gaseous constituents. At Franklin, water containing about 300 parts of bicarbonate is regarded as poor for high pressure boiler feed.

TABLE C.—*Analyses of ground waters from wells in the belt of soft bicarbonate waters*
(Parts per million)

Well No.	1	2	3	4	5	6
County	Arlington	Fairfax	Prince William	Caroline	Westmoreland	Westmoreland
Town	Alexandria	Mt. Vernon	Quantico	Port Royal	Colonial Beach	Washington's Birthplace
Depth (feet)	300	525	360	315	585	380
Water-bearing rocks	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous	Upper (?) Cretaceous	Paleocene (?)	Paleocene (?)
Silica (SiO_2)	48	24	35	...	...	12
Iron (Fe)	.04	.04	Tr.	...	...	.08
Calcium (Ca)	1.4	.5	2.4	...	...	3.4
Magnesium (Mg)	4	.3	1.3	...	...	2.3
Sodium (Na)	22	69	27	...	...	143
Potassium (K)	3.4	1.4		...	...	8.7
Bicarbonate (HCO_3)	50	164	63	125	245	400
Sulfate (SO_4)	11	6.7	12	20	14	8.0
Chloride (Cl)	3.0	10	3.9	1	1	2.5
Fluoride (F)	...	...	...	.2	1.5	1.3
Nitrate (NO_3)	.36	.05	...	.2	.2	.10
Free carbon dioxide (CO_2)	...	...	...	6.1	5.0	...
Total dissolved solids	116	192	108	...	...	381
Total hardness (as $CaCO_3$)	5.1	2.5	11	4.5	6	18
Analyst[a]	SKL	SKL	RBR	EWL	EWL	EWL
Date of collection	Oct. 21, 1931	Apr. 8, 1932	Mar. 5, 1931	Jan. 1, 1944	Jan. 1, 1944	Oct. 12, 1933

[a] SKL = S. K. Love, RBR = R. B. Rudy, EWL = E. W. Lohr.

TABLE C.—*Analyses of ground waters from wells in the belt of soft bicarbonate waters—Continued*

(Parts per million)

Well No.	7	8	9	10	11	12
County	Westmoreland	Westmoreland	Westmoreland	Westmoreland	Northumberland	Northumberland
Town	Oak Grove	Leedstown	Leedstown	Montross	Lewisetta	Lewisetta
Depth (feet)	530	214	500	648	325	550
Water-bearing rocks	Paleocene (?)	Eocene	Paleocene (?)	Paleocene (?)	Paleocene (?)	Paleocene (?)
Silica (SiO_2)	...	11	11	18	31	24
Iron (Fe)	...	.33	.03	.06	.67	.10
Calcium (Ca)	...	5.4	2.2	.8	5	2.1
Magnesium (Mg)	...	4.0	1.8	.8	6.7	1.7
Sodium (Na)	...	154	171	130[a]	107	177
Potassium (K)	...	12	9.0			
Bicarbonate (HCO_3)	280	447	472	324	301	456
Sulfate (SO_4)	7	11	11	10	7.6	18
Chloride (Cl)	1	3.5	2.0	2.8	3.5	3.9
Fluoride (F)	1.6	1.7	1.7	2.6	...	...
Nitrate (NO_3)	.2	.0	.0	.4	1.9	.61
Free carbon dioxide (CO_2)	...	...	...	...	...	...
Total dissolved solids	...	421	444	326	311	459
Total hardness (as $CaCO_3$)	6	30	13	5.5	40	12
Analyst[b]	EWL	EWL	EWL	EWL	ATG	ATG
Date of collection	Oct. 12, 1944	Oct. 14, 1944	Oct. 14, 1944	Jan. 1, 1944	July 5, 1918	July 5, 1918

[a] In sample collected Feb. 13, 1941.
[b] EWL = E. W. Lohr, ATG = A. T. Geiger.

TABLE C.—*Analyses of ground waters from wells in the belt of soft bicarbonate waters—Continued*
(Parts per million)

Well No.	13	14	15	16	17	18
County	Northumberland	Northumberland	Lancaster	Lancaster	Lancaster	Caroline
Town	Reedville	Reedville	Taft	Irvington	Kilmarnock	Port Royal
Depth (feet)	680	680	680	750	610	315
Water-bearing rocks	Eocene	Eocene	Eocene	Paleocene (?)	Eocene	Paleocene (?)
Silica (SiO_2)	25	37	...	...	34	...
Iron (Fe)	.40	Tr.	...	...	.07	...
Calcium (Ca)	2	2.4	...	...	3.1	...
Magnesium (Mg)	1.3	3.0	...	...	1.9	...
Sodium (Na), Potassium (K)	201	230	...	...	...	...
Bicarbonate (HCO_3)	486	551	512	441	484	125
Sulfate (SO_4)	35	37	34	40	37	20
Chloride (Cl)	8	8	33	11	11	1
Fluoride (F)	...	...	3.8	2.3	2.7[a]	.2
Nitrate (NO_3)	.6	.75	...	...	.61	.2
Free carbon dioxide (CO_2)	...	...	...	...	...	6.1
Total dissolved solids	525	594	...	...	526	...
Total hardness (as $CaCO_3$)	10	18	6	6	16	4.5
Analyst[b]	HBR	HBR	MDF&LWM	MDF&LWM	ATG	EWL
Date of collection	July 2, 1918	July 1, 1918	Feb. 27, 1941	Feb. 28, 1941	July 5, 1918	Jan. 1, 1944

[a] In sample collected Feb. 13, 1941.
[b] HBR = H. B. Riffenburg, MDF&LWM = M. D. Foster and L. W. Miller, ATG = A. T. Geiger, EWL = E. W. Lohr.

TABLE C.—*Analyses of ground waters from wells in the belt of soft bicarbonate waters—Continued*
(Parts per million)

Well No.	19	20	21	22	23	24
County	Essex	Essex	Middlesex	Middlesex	Middlesex	King William
Town	Tappahannock	Tappahannock	Water View	Remlik	Urbanna	Nelson Bridge
Depth (feet)	500	265	305	471	480	200
Water-bearing rocks	Paleocene (?)	Eocene	Eocene	Eocene	Eocene	Eocene
Silica (SiO_2)	...	...	30	...	...	...
Iron (Fe)	...	...	Tr.	...	...	...
Calcium (Ca)	...	3.2	7.2	...	15	...
Magnesium (Mg)	...	1.6	3.7	...	6.6	...
Sodium (Na) } Potassium (K) }	...	159	113	...	200	...
Bicarbonate (HCO_3)	404	497	322	480	571	162
Sulfate (SO_4)	8	8.2	13	13	20	18
Chloride (Cl)	2	2	3	5	6	10
Fluoride (F)	2.1	...	1.0[a]	2.3	2.2[a]	.2
Nitrate (NO_3)	...	...	.54	...	.5	.0
Free carbon dioxide (CO_2)	...	...	...	...	...	5.8
Total dissolved solids	...	461	328	...	547	...
Total hardness (as $CaCO_3$)	9	13.6	33	9	65	12
Analyst[b]	MDF	ATG	HBR	MDF	HBR	EWL
Date of collection	Feb. 13, 1941	July 24, 1918	Jan. 28, 1921	Feb. 13, 1941	June 5, 1918	Dec. 31, 1943

[a] In sample collected Feb. 13, 1941.
[b] MDF = M. D. Foster, HBR = H. B. Riffenburg, EWL = E. W. Lohr.

TABLE C.—*Analyses of ground waters from wells in the belt of soft bicarbonate waters—Continued*
(Parts per million)

Well No.	25	26	27	28	29	30
County	King William	King and Queen	King and Queen	King William	King William	King William
Town	Aylett	Walkerton	Walkerton	Manquin	Cohoke	West Point
Depth (feet)	368	214	365	200	375[a]	379
Water-bearing rocks	Paleocene (?)	Eocene	Paleocene (?)	Eocene	Paleocene (?)	Eocene
Silica (SiO_2)	.....	17	32	.....	.....	21
Iron (Fe)	.....	.02	.01	.....	.....	.05
Calcium (Ca)	.....	3.8	.6	.....	.....	1.8
Magnesium (Mg)	.....	1.6	.5	.....	.....	.6
Sodium (Na)	.....	160	88	.....	.....	181
Potassium (K)	.....			.....	.....	6.6
Bicarbonate (HCO_3)	165	412	215	154	223	458
Sulfate (SO_4)	17	14	11	20	5	12
Chloride (Cl)	1	4.0	2.2	1	3	11
Fluoride (F)	.3	2.2	1.7	.4	.5	3.1
Nitrate (NO_3)	.1	.0	.0	.3	.3	.47
Free carbon dioxide (CO_2)	4.0	1.8	4.3	.....	.....	.....
Total dissolved solids	.....	404	242	.....	.....	461
Total hardness (as $CaCO_3$)	4.5	16	3.6	12	52	7.0
Analyst[b]	EWL	EWL	EWL	EWL	EWL	MDF&LWM
Date of collection	Jan. 25, 1944	Dec. 31, 1943	Dec. 31, 1943	Sept. 3, 1943	Sept. 2, 1943	Feb. 10, 1941

[a] Depth may be in error.
[b] EWL = E. W. Lohr, MDF&LWM = M. D. Foster and L. W. Miller.

TABLE C.—*Analyses of ground waters from wells in the belt of soft bicarbonate waters—Continued*
(Parts per million)

Well No.	31	32	33	34	35	36
County	Gloucester	New Kent	New Kent	Charles City	Charles City	James City
Town	Freeport	Mountcastle	Providence Forge	Malvern Hill	Charles City	Jamestown
Depth (feet)	330	328	286	180	260	311
Water-bearing rocks	Eocene	Paleocene (?)	Paleocene (?)	Lower Cretaceous	Eocene	Eocene
Silica (SiO_2)	...	...	33	...	...	...
Iron (Fe)	...	...	.02	...	...	.10
Calcium (Ca)	...	...	2.0	...	...	4.2
Magnesium (Mg)	...	...	1.0	...	...	6.6
Sodium (Na)	...	...	101	...	...	149
Potassium (K)	...	...		...	...	
Bicarbonate (HCO_3)	717	230	253	183	270	384
Sulfate (SO_4)	1	7	15	7	7	7.6
Chloride (Cl)	36	5	1.9	3	12	9.6
Fluoride (F)	3.5	1.5	1.1	.4	1.8	3.6[a]
Nitrate (NO_3)	...	.0	.0	.4	.0	.39
Free carbon dioxide (CO_2)	...	...	3.6	2.9	...	...
Total dissolved solids	...	...	279	...	...	488
Total hardness (as $CaCO_3$)	21	4.5	9.1	39	12	38
Analyst[b]	MDF	EWL	EWL	EWL	EWL	ATG
Date of collection	Feb. 13, 1941	Sept. 25, 1943	Dec. 29, 1943	Dec. 29, 1943	Sept. 10, 1943	Oct. 18, 1918

[a] In sample collected Feb. 6, 1941.
[b] MDF = M. D. Foster, EWL = E. W. Lohr, ATG = A. T. Geiger.

TABLE C.—*Analyses of ground waters from wells in the belt of soft bicarbonate waters—Continued*
(Parts per million)

Well No.	37	38	39	40	41	42	43
County	Prince George	Nansemond	Nansemond	Isle of Wight	Southampton	Southampton	Southampton
Town	Brandon	Suffolk	Cypress	Franklin	Franklin	Franklin	Courtland
Depth (feet)	190	717	420	600	359	150	230
Water-bearing rocks	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous	Upper (?) Cretaceous	Lower Cretaceous
Silica (SiO_2)	38	21	9.9	31	....	11	32
Iron (Fe)	.03	.20	.07	.02	....	.01	.0
Calcium (Ca)	1.9	2.3	2.3	.3	....	1.5	.5
Magnesium (Mg)	.5	.8	3.3	.3	....	1.3	.3
Sodium (Na)	83	213	311	102	....	150	90
Potassium (K)	4.6	6.7	12	4.5	....	11	6.4
Bicarbonate (HCO_3)	221	518	775	233	277	419	196
Sulfate (SO_4)	5.2	13	16	9.5	7	2.6	12
Chloride (Cl)	5.8	25	26	10	4.0	3.0	16
Fluoride (F)	.7	6.4[a]	6.4	6.6	4.6	2.1	5.5
Nitrate (NO_3)	.15	.06	2.5	.15	.38	.0	.20
Free carbon dioxide (CO_2)	7.6	2.9[a]	....	3.8[b]	4.4[c]	....	....
Total dissolved solids	240	549	782	282	....	395	269
Total hardness (as $CaCO_3$)	6.8	9.0	19	2.5	5	9.1	2.5
Analyst[d]	MDF	WLL	MDF	MDF&LWM	MDF	WMN	WMN
Date of collection	Oct. 3, 1939	Sept. 14, 1929	Aug. 4, 1939	Nov. 27, 1941	Sept. 15, 1937	Apr. 18, 1938	Apr. 20, 1938

[a] In sample collected Aug. 4, 1944.
[b] In sample collected Aug. 2, 1944.
[c] In sample collected Aug. 4, 1944.
[d] MDF = M. D. Foster, WLL = W. L. Lamar, MDF&LWM = M. D. Foster and L. W. Miller, WMN = W. M. Noble.

In Lancaster and Northumberland counties, the bicarbonate content does not exceed 550 parts per million. Around the western reentrant made by the high-chloride zone in James City County, the bicarbonate in places may be lower than 400 parts. Along the south bank of James River, the bicarbonate content reaches a maximum of about 500 parts per million within the soft water belt in northern Nansemond County, but in southern Nansemond County it rises to almost 800 parts.

In several widely separated localities, where comparative data are available, it was found that the water from deeper wells contains less bicarbonate (and hence less total mineralization) than that from shallower wells. It does not seem to make much difference whether or not formational boundaries are crossed in the artesian system. Water from Upper Cretaceous sands contains more bicarbonate than that from Lower Cretaceous beds (Table C, 41, 42); water from higher (Eocene) sands contains more bicarbonate than water from wells penetrating deeper (Paleocene (?)) beds (15-16, 19-20, 26-27); and water from sands high in the Potomac group (40-41) contains more bicarbonate than water from deeper horizons. In the analyses cited, the deeper samples contain from 50 to 200 parts less than samples from higher strata.

At Lake Prince, Nansemond County, where only test well samples, which might not have been truly representative, were available, there was a slight increase of bicarbonate content with depth. At Manquin, King William County, and Leedstown (Table C, 8-9) there is slight increase of bicarbonate with depth.

In northern Charles City County, samples from highest Eocene strata have about the same bicarbonate as those from somewhat deeper beds, but water from Paleocene (?) sediments contains a little less bicarbonate. At West Point no differences were apparent in water from relatively shallow and rather deep wells. This latter area is highly developed by industrial wells and there is at least a possibility of migration of water from deeper to higher horizons.

Fluoride.—Fluoride is a constituent of much importance in the sodium-bicarbonate waters, since it commonly occurs in harmful amounts, more than 1 part per million.[11] In places the fluoride is more than 4 parts per million. At this concentration, 100 per cent incidence of mottled enamel of teeth of children up to 10 years of age who habitually drink these waters results. Conversely, small amounts of fluoride are of importance since it has been shown[12] that concentrations up to 1 part per million tend to inhibit dental decay.

It has been shown above that little or no fluoride is present in waters of the hard water belt. The few analyses of water from wells penetrating granitic rock along the Fall Zone show that it is present in places in high concentrations in waters obtained from such wells.

East of the hard water boundary, however, fluoride appears commonly in concentrations greater than 1 part per million (Fig. 8). South of James River, fluoride rises to 4 or 5 parts per million immediately east of the hard water belt at Courtland (Table C, 43), but along James River the increase is more gradual. In the York-James Peninsula (Table C, 32-35), and in the northern part of the Coastal Plain (Table C, 4-9), the fluoride content remains very low for about 10 miles east of the boundary of the hard water belt and then increases rather gradually eastward.

Although high at the western border of the soft bicarbonate water belt south of James River, the fluoride content increases farther eastward and concentrations of 5 or more parts per million are commonly present. In southern Nansemond County, several wells yield water containing 6 parts or more (Table C, 38, 39). The maximum amount of fluoride found in any Virginia Coastal Plain water, 7.5 parts per million, was from a well at Suffolk. In the York-James Peninsula, the maximum found outside the zone of high chloride water was 4.4 parts at Jamestown. In the Northern Neck, the fluoride is rarely more than 3 parts per million (Table C, 10, 15-17).

In general the fluoride content increases with depth, although analyses from a few places (Table C, 26-27) indicate that this rule is not invariable. The increase of fluoride with depth takes place whether or not the two samples compared are from the same formation, or from different formations. At Franklin, water from Upper (?) Cretaceous strata contains 2.1 parts per million of fluoride, but the uppermost Potomac strata yield water containing 4.6 parts per million. Water from still deeper Potomac strata contains 6.6 parts per million. (See Table C, 40, 41, 42.) Such large differences are uncommon. From a regional point of view, it may be noted that in the area north of James River, where wells develop water in Eocene and Paleocene (?) beds, the fluoride reaches a maximum of 4.5 parts per million, but in the area south of James River, where

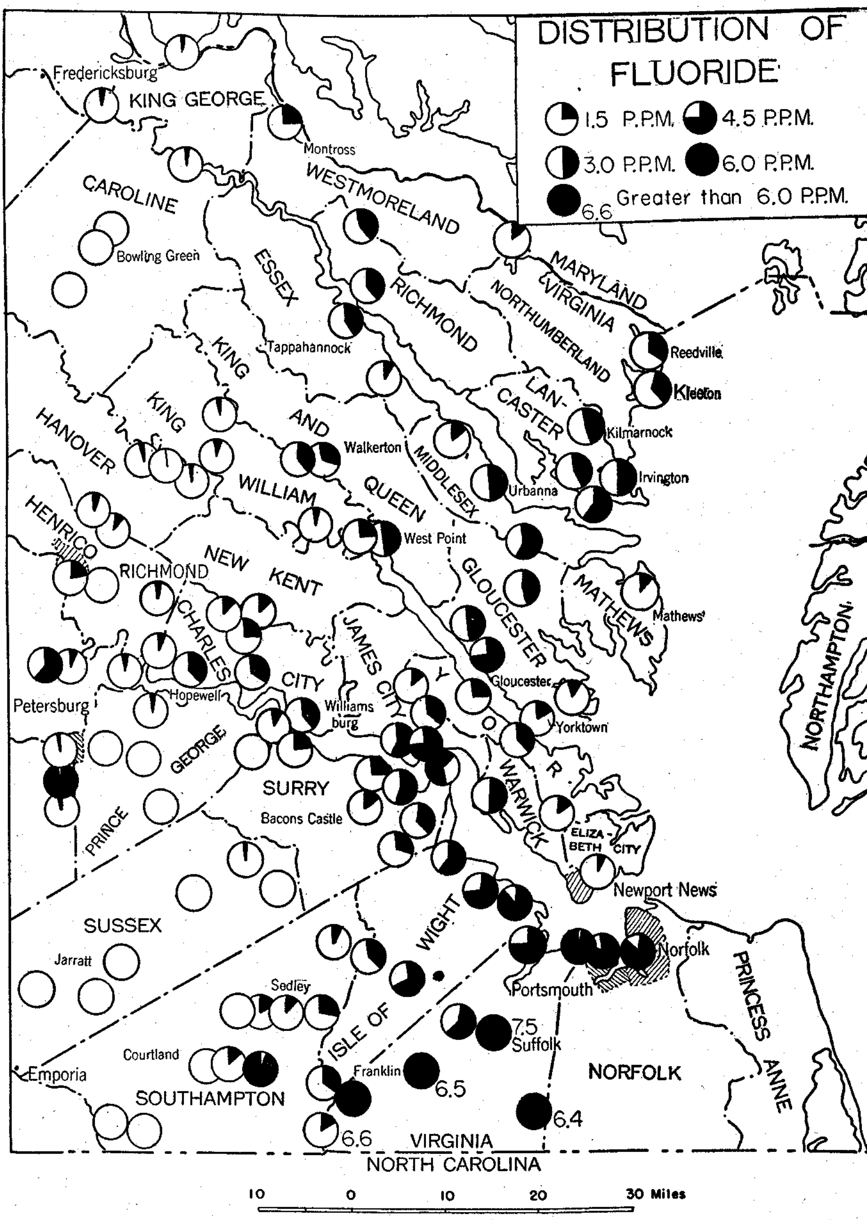


FIGURE 8.—Map showing distribution of fluoride in artesian waters in eastern Virginia.

wells generally penetrate Lower Cretaceous beds, the fluoride may be as high as 7.5 parts per million.

The source of fluoride found in the Virginia Coastal Plain waters is not known, but a number of possible sources are discussed in a previous publication.[6]

Other constituents.—The chloride content in the soft bicarbonate belt is almost everywhere less than 20 parts per million, and in many places it is less than 10 parts per million. Near the border of the high-chloride belt, samples may commonly contain from 20 to 40 parts per million (Table C, 15, 31, 38, 39). In the belt of low-chloride sodium-bicarbonate waters, there is not the progressive eastward increase in chloride which is characteristic of the bicarbonate and fluoride; neither is there a marked change in chloride content with depth. In this zone the chloride in water from deeper wells is generally only 3 or 4 parts greater than in water from wells drawing upon shallower sands (Table C, 11-12, 16-17) or may even decrease slightly with depth (8-9, 26-27).

Softening by base exchange.—Base exchange, the process by which one cation in solution may be exchanged for other cations held by substances such as some clay minerals, is a process of great importance to the ground waters in the Virginia Coastal Plain. Because of this phenomenon, the artesian waters in the areas of prolific water-bearing beds are sodium-bicarbonate waters particularly suited to the domestic purposes for which they are generally used and to certain industrial uses, instead of being less desirable hard waters with marked scale-forming and soap-consuming qualities.

Base exchange is a widely known process. The mechanism of the process has been recently restated as follows:[17] "The substitution of even small amounts of bivalent magnesium for trivalent aluminum, and of trivalent aluminum for tetravalent silicion, results in a valency deficiency within the crystal lattice. This deficiency is compensated by ions that are held between the crystal sheets and are the so-called exchangeable bases."

Glauconite, the active ingredient in one type of widely used water softener, is present in abundance in the Eocene strata in eastern Virginia, and the immediate thought might be that this mineral is of primary importance in softening waters which move eastward down dip from the hard water belt. However, glauconite is not present in deposits of the Potomac group. Moreover, water occurring hundreds of feet below the base of the glauconite-bearing Eocene beds, and which presumably had had little or no contact with glauconitic beds, is softened as completely as water occurring near the top of the Potomac group. In at least three places, water from a greater depth, with the same bicarbonate content as water from a lesser depth, is much softer than the water from a lesser depth. Hence it seems evident that material other than the glauconite, undoubtedly clayey minerals,[14, 17] is functioning as a base exchange agent. It is not implied, however, that glauconite is not an effective softening agent in those places where ground waters do come in contact with it.

Sulfate is low in the zone of soft bicarbonate waters. In most places it ranges from less than 1 part to about 20 parts per million (Figs. 3-6). It may be noted that the sulfate is scarcely higher than is generally found along the Fall Zone. It is less than that found in a few samples taken along or near the Fall Zone which are somewhat more highly mineralized than the average sample.

Origin of the bicarbonate.—It has been shown that waters near the Fall Zone contain free carbon dioxide and that, as they travel eastward down dip, the waters increase in calcium bicarbonate content due to the reaction of the free carbon dioxide with calcareous material. A maximum of about 250 parts per million of bicarbonate may be accounted for thereby. At no very great distance from the Fall Zone, the carbon dioxide is entirely converted to bicarbonate and presumably further solution of calcium carbonate can not take place. In fact, the graph of the bicarbonate content indicates an area of no increase in bicarbonate east of the area where a large initial increase occurs. Upon reaching the soft water zone, however, the waters again begin to gain in bicarbonate, the continued gain in bicarbonate being a progressive addition as sodium bicarbonate.

The origin of the bicarbonate gained in the soft water zone has been dealt with in previous publications[6, 7] and will not be considered in detail here. Briefly, it is thought that sulfate in the artesian waters is broken down by chemical or biochemical action of organic matter in the sediments, with the consequent release of free carbon dioxide (Table C, 4, 18, 24, 33, 37). The liberated carbon dioxide then reacts with limy sediments to form calcium bicarbonate which in turn is converted, by base exchange, to sodium bicarbonate.

HIGH-CHLORIDE BELT

East of the belt of soft sodium-bicarbonate water, ground waters are also of the sodium-bicarbonate type but contain more than 40 parts per million of chloride, resulting from contamination of large amounts of meteoric water by small amounts of marine water. The boundary of this belt extends from the southeastern tip of the Northern Neck southwestward to about Toano, James City County, and from there southeastward through northern Nansemond County (Fig. 1).

The zone of high-chloride water has been described in detail in a recent paper[3] by the writer and hence the factual data will be only briefly summarized here.

South of James River, the water-bearing beds are largely of early Cretaceous age, but north of James River the Eocene section thickens from less than 100 to a maximum of 400 feet. Northward the formations rise gently; hence the high-chloride area appears to be a structural trough where poor artesian circulation has failed to flush out all of the sea water with which the sediments were once saturated.

Along the inner border of the belt of high-chloride waters the chloride is lowest (Table D, 1, 4, 9, 14, 20), but the chloride content rises with distance eastward from the Fall Zone and also becomes higher towards the center of the wedge-shaped area of high-chloride waters at equal distances from the Fall Zone.

Along the border of the high-chloride belt, the chloride content is commonly less than 250 parts per million, the maximum amount generally regarded as desirable for public supplies, and the water is used successfully for municipal supplies, as at Williamsburg (Table D, 10). In fact, water containing up to 400 parts per million is used or has been used with more or less success for public supplies at Gloucester Court House, Yorktown, Camp Peary (near Williamsburg), and Fort Eustis (Table D, 5, 7, 8, and 12). Water containing up to 400 parts of chloride foams badly in boilers, probably due as much to the high bicarbonate content as to the chloride content. Water at Williamsburg, which contains 225 parts per million of chloride, is said to be very corrosive in hot water boilers and slightly corrosive when cold.

Away from the borders of the belt, the chloride content increases and, in several wells, the water obtained ranges from 1,000 to 2,000 parts per million (Table D, 2, 6, 11, 16, 18). At Old Point Comfort, water containing 4,500 parts per million has been reported.

At every place where comparative data are available, it has been found that water from deeper strata has a higher chloride content than water from shallower wells at the same place. This is particularly marked along the border of the belt, where wells which tap the uppermost artesian sands yield water containing as little as 10 or 20

TABLE D.—*Analyses of ground waters from wells in the belt of high-chloride waters*
(Parts per million)

Well No.	1	2	3	4	5
County	Lancaster	Middlesex	Mathews	Gloucester	Gloucester
Town	Palmer	Amburg	North	Capahosic	Gloucester
Depth (feet)	580	822	460	404	810
Water-bearing rocks	Eocene	Paleocene (?)	Eocene	Eocene	Paleocene (?)
Silica (SiO_2)	...	57	52	33	17
Iron (Fe)	...	8.0	...	0	.09
Calcium (Ca)	...	9	8.4	1.2	4.6
Magnesium (Mg)	...	20	8.3	1.1	1.9
Sodium (Na)	...	1646	711	302	528
Potassium (K)	...				16
Bicarbonate (HCO_3)	470	1051	920	692	773
Sulfate (SO_4)	40	234	65	18	60
Chloride (Cl)	113	1820	550	54	345
Fluoride (F)	3.7	...	1.0[a]	4.3[b]	2.8
Nitrate (NO_3)	...	5.0	1.2	1.2	.89
Free carbon dioxide (CO_2)	...	...	...	...	...
Total dissolved solids	...	4308	1881	775	1356
Total hardness	8	104	55	8	19
Analyst[c]	MDF&LWM	HBR	HBR	HBR	MDF&LWM
Date of collection	Feb. 28, 1941	June 11, 1918	June 14, 1918	June 19, 1918	Feb. 12, 1941

[a] In sample collected Feb. 13, 1941.
[b] In sample collected Feb. 12, 1941.
[c] MDF&LMW = M. D. Foster and L. W. Miller, HBR = H. B. Riffenburg.

TABLE D.—*Analyses of ground waters from wells in the belt of high-chloride waters—Continued*
(Parts per million)

Well No.	6	7	8	9	10
County	Gloucester	York	York	James City	James City
Town	Achilles	Yorktown	Camp Peary	Norge	Williamsburg
Depth (feet)	600?	480	446	419	417
Water-bearing rocks	Eocene	Eocene	Eocene (?)	Eocene	Eocene
Silica (SiO_2)	...	...	15	40	...
Iron (Fe)	...	...	.37	6	...
Calcium (Ca)	10	...	5.2	11	...
Magnesium (Mg)	20	...	2.5	3.1	...
Sodium (Na)	1404	...	356	252	...
Potassium (K)			9.1		
Bicarbonate (HCO_3)	936	454	404	365	434
Sulfate (SO_4)	207	54	46	39	27
Chloride (Cl)	1540	522	305	176	255
Fluoride (F)	...	2.3	1.5	...	2.1
Nitrate (NO_3)	Tr.	...	.0	...	...
Free carbon dioxide (CO_2)	...	...	...	...	...
Total dissolved solids	3777	...	945	718	...
Total hardness	107	22	24	40	15
Analyst[a]	HBR	MDF	EWL	F & R	MDF&LWM
Date of collection	June 19, 1918	Feb. 7, 1941	Feb. 12, 1943	1910	Feb. 7, 1941

[a] HBR = H. B. Riffenburg, MDF = M. D. Foster, EWL = E. W. Lohr, F & R = Froehling & Robertson, MDF&LWM = M. D. Foster and L. W. Miller.

TABLE D.—*Analyses of ground waters from wells in the belt of high-chloride waters—Continued*
(Parts per million)

Well No.	11	12	13	14	15
County	Warwick	Warwick	Warwick	Warwick	Warwick
Town	Lee Hall	Ft. Eustis	Camp Patrick Henry	Mulberry Island	Morrison
Depth (feet)	475	550	492	417	760
Water-bearing rocks	Eocene	Eocene (?)	Eocene	Eocene	Paleocene (?)
Silica (SiO_2)	...	17	...	...	...
Iron (Fe)	...	.21	18	Tr.	...
Calcium (Ca)	...	4.5	...	4.0	...
Magnesium (Mg)	...	2.3	...	4.5	...
Sodium (Na)	...	454	...	390	...
Potassium (K)	...	9.0	...		...
Bicarbonate (HCO_3)	546	475	724	621	452
Sulfate (SO_4)	112	56	300	58	52
Chloride (Cl)	1050	408	2200	216	660
Fluoride (F)	1.4	2.9	.9	...	2.2
Nitrate (NO_3)	...	.8	...	Tr.	...
Free carbon dioxide (CO_2)	...	...	...	...	...
Total dissolved solids	...	1201	...	1130	1650
Total hardness	40	20	240	28	24
Analyst[a]	MDF	EWL	EWL	HBR	MDF
Date of collection	Nov. 21, 1941	July 7, 1942	Oct. 16, 1942	Oct. 15, 1918	Feb. 26, 1942

[b] MDF = M. D. Foster, EWL = E. W. Lohr, HBR = H. B. Riffenburg.
Well 15 at Mariners Museum.

TABLE D.—*Analyses of ground waters from wells in the belt of high-chloride waters—Continued*
(Parts per million)

Well No.	16	17	18	19	20
County	Warwick	Warwick	Warwick	Norfolk	Nansemond
Town	Newport News	Newport News	Newport News	Norfolk	Drivers
Depth (feet)	820	900	400	720	550
Water-bearing rocks	Paleocene (?)	Paleocene (?)	Eocene (?)	Upper Cretaceous	Upper Cretaceous (?)
Silica (SiO_2)	...	...	...	...	...
Iron (Fe)	...	...	...	...	...
Calcium (Ca)	...	...	...	...	...
Magnesium (Mg)	...	...	...	...	...
Sodium (Na)	...	...	...	528	...
Potassium (K)	...	...	...		...
Bicarbonate (HCO_3)	686	614	1184	616	544
Sulfate (SO_4)	80	75	135	65	25
Chloride (Cl)	1680	690	1080	408	67
Fluoride (F)	.9	1.2	1.2	4.8	7.4
Nitrate (NO_3)	...	...	.6	...	...
Free carbon dioxide (CO_2)	4.3	...	1.4	1.4	5.0
Total dissolved solids	...	...	...	...	...
Total hardness	76	22	144	12	7.5
Analyst[a]	MDF&WMN	MDF&LWM	DMD	MDF&GJP	MDF
Date of collection	Aug. 5, 1940	Dec. 12, 1940	May 31, 1944	Aug. 31, 1939	Oct. 4, 1939

[a] MDF&WMN = M. D. Foster and W. M. Noble, MDF&LWM = M. D. Foster and L. W. Miller, DMD = D. M. Derrick, MDF&GJP = M. D. Foster and G. J. Petretic, MDF = M. D. Foster.

Well 16 at Buxton Hospital, 17 at Levinson Meat Packing Co., 18 at Gas Works.

parts per million of chloride and water from deeper horizons may contain 100 or more parts of chloride.

The probability of increase of chloride content is a question of great importance in areas where such increases are possible. It has been shown[3] that, in eastern Virginia, slight increases of chloride content have occurred in a few places where the amount of withdrawal of water from the ground exceeded the amount of recharge from the west. At Fort Eustis, a temporary increase in chloride content was accompanied by continued decline of water levels in observation wells, at which time more brackish waters migrated to the well field from down dip or from depth.

Certain wells show a very erratic behavior in regard to the chloride content of the water yielded. During periods of idleness or very little discharge, these wells yield water of relatively low chloride content, but, upon heavy pumping, the chloride content of the water rises immediately to a higher amount and remains at that level (Fig. 9). The most important consideration in this connection is that this limited increase should not be mistaken for the slow gradual increase

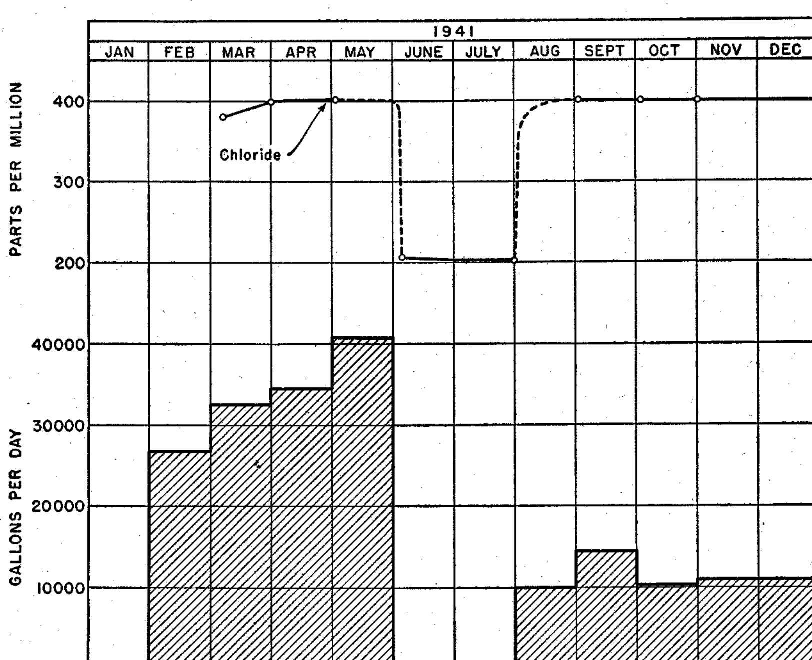


FIGURE 9.—Diagram showing relation of chloride content of artesian water to amount of pumping at Yorktown, Virginia.

which will occur with overpumping and which may continue as long as overpumping continues.

The geologic conditions responsible for limited rises in chloride content in well waters after periods of idleness may only be surmised. It is thought that fresh water may enter the area from the west along thin, more permeable channelways and, because of its low specific gravity, may tend to be trapped and form a fresh water "pool" above the saline waters instead of diffusing through the stratum, just as oil pools occur in stratigraphic or structural traps. At a low rate of pumping, the water yielded would then be largely fresh water but, upon pumping at a higher rate, the fresh water "pool" is exhausted and the water yielded is almost entirely the characteristic high-chloride water of the area.

As mentioned above, water containing up to 400 parts of chloride has been used successfully for public supplies. At Newport News, water containing 690 parts of chloride (Table D, 17) has been used for cooling purposes, although the water is corrosive. It is reported that, within three years of installation, the pump column corroded completely through and fell to the bottom of the well. In one place, hot water containing about 500 parts of chloride was found to be extremely corrosive. An old, but still serviceable, boiler at the Yorktown Naval Mine Depot was rendered entirely useless within a few days after high-chloride water (Table D, 7) was used for feed during a water shortage in the drought of 1941.

Bicarbonate.—The bicarbonate content ranges from about 500 to about 900 parts per million with few exceptions (Table D, 18), and is therefore only slightly greater than the maximum found in soft low-chloride bicarbonate waters. The progressive increase in bicarbonate content is not maintained in the high-chloride zone because of the increasing admixture of marine waters which are characteristically low in bicarbonate.

Sulfate.—Sulfate is high in these waters in contrast to water in the belts to the west because of the admixture of marine water which is high in sulfate. It ranges from 25 to 300 parts per million in the analyses given in Table D.

Hardness.—The hardness of the high-chloride waters ranges from less than 10 parts to more than 200 parts per million. In general, those samples containing low chloride have a low hardness, but those with a high chloride content have a high total hardness because the sea water, with which they are contaminated, contains much hardness.

A number of samples contain more magnesium than calcium. This is expected where water of meteoric origin has been contaminated by sea water. The majority of samples, however, contain somewhat more calcium than magnesium and have a lower total hardness than would be expected if the waters were a simple mixture of meteoric and marine waters. The origin of this type of water has been discussed in another paper.[7]

Fluoride.—Fluoride in the high-chloride belt is about the same as in the soft bicarbonate belt immediately to the west; apparently the progressive eastward increase in fluoride content is compensated for by dilution with the connate marine water.

WATER FROM MIOCENE AND MIDDLE EOCENE DEPOSITS

Many wells from 30 to 150 feet deep obtain water from sands or shell and sand strata of the Yorktown formation of Miocene age in the area bordering Chesapeake Bay. The Yorktown formation generally contains one or more permeable strata yielding fresh water under low artesian head. Deeper wells reaching sands of the Calvert yield water which is more or less brackish. Inland most shallow drilled wells obtain water from the Nanjemoy formation of Middle Eocene age.

Most of the wells are small-diameter jetted or driven wells, but a few are drilled. A few dug wells reach Miocene deposits.

Most of the wells tapping Miocene strata supply homes, but a few furnish water to small industries and to small Army and Navy establishments. In the Norfolk area, several large farms are irrigated by water from these deposits.[6] Nanjemoy deposits furnish water to homes, but at West Point about 1,000 gallons a minute is pumped from this formation for industrial use.

CHEMICAL CHARACTER

These waters are a moderately hard calcium-bicarbonate type. The total hardness of about half the samples for which analyses are available ranges from 100 to 200 parts per million; one-fourth contain less than 100 parts of hardness and about one-fourth contain from 200 to 400 parts.

Some of the softer Miocene waters simply have a low mineral content, as samples from Chincoteague and Lynnhaven (Table E, 22, 27), but a few others having a low hardness (Table E, 3, 4, 11) contain a rather large amount of sodium bicarbonate and are hard waters which have been softened by base exchange. This type of water is characteristic of the Nanjemoy formation.

Hard or moderately hard waters are characteristic of the Yorktown formation. In most waters from the Yorktown formation, calcium and magnesium are present only as bicarbonate, and excess bicarbonate is present as sodium bicarbonate, indicating that some base exchange has taken place, as in samples from Urbanna, Naxera and Yorktown (Table E, 5, 7, 17).

High sulfate is present in a few very hard waters. (Table E, 7, 9, 10). Where more than 100 parts of sulfate is found, it is generally present as calcium sulfate (Table E, 9, 24 and New Point Comfort, Fig. 10). These waters therefore contain sulfate of permanent hardness, in addition to temporary or bicarbonate hardness. A sample from Gloucester County (Table E, 7), however, contains 100 parts per million sulfate as sodium sulfate.

Chloride is generally low in water from the Yorktown formation, but in coastal areas it may commonly range up to 100 parts.

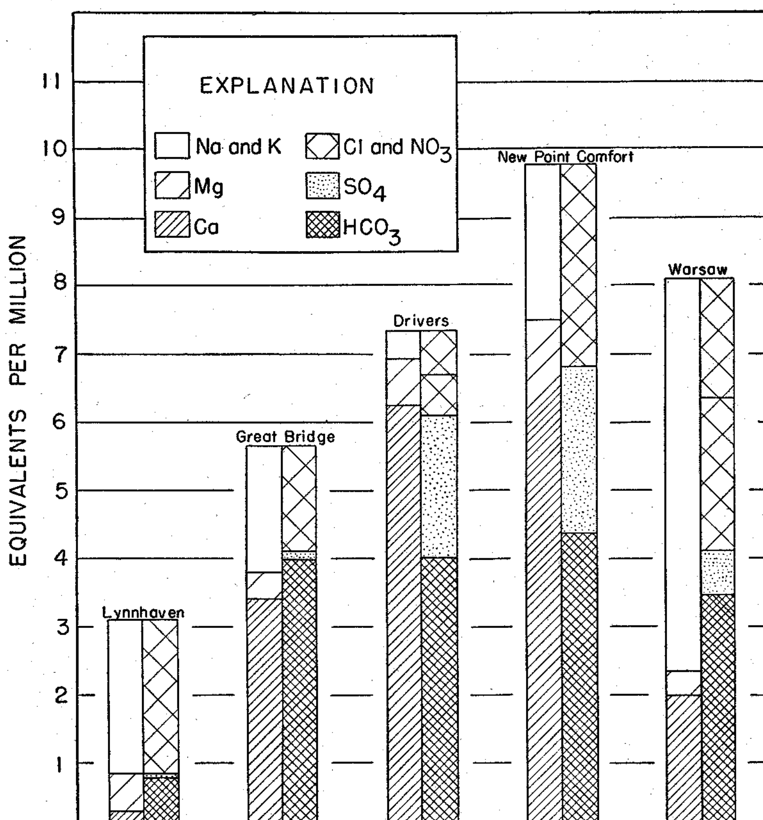


FIGURE 10.—Diagram showing composition of several types of water from Yorktown formation of Miocene age in eastern Virginia.

or even higher, as at Big Bethel (Table E, 19), Dam Neck (29), and New Point Comfort (10), where the chloride is respectively 109, 290, and 103 parts per million. The chloride has originated locally as salt spray carried down with rainfall.

In a few inland localities the chloride is high in shallow wells in the Miocene, as at Warsaw, Richmond County (Table E, 2, and Fig. 10), where it is 81 parts per million. Here high chloride is

TABLE E.—*Analyses of ground waters from Miocene and Middle Eocene formations*
(Parts per million)

Well No.	1	2	3	4	5	6
County	Northumberland	Richmond	Essex	Essex	Middlesex	King and Queen
Town	Heathsville	Warsaw	Bowlers Wharf	Wares Wharf	near Urbanna	Court House
Depth (feet)	50	40	168	180	?	145
Water-bearing rocks	Yorktown	Yorktown	Nanjemoy	Nanjemoy	Yorktown (?)	Nanjemoy (?)
Silica (SiO_2)	...	11	...	38	...	...
Iron (Fe)	...	1.1	0.7	.07	...	...
Calcium (Ca)	20	40	6.1	25	56	...
Magnesium (Mg)	10	14	6.2	1.1	24	...
Sodium (Na), Potassium (K)	60	135[a]	82[a]	93[a]	116[a]	...
Bicarbonate (HCO_3)	149	212	233	302	555	205
Sulfate (SO_4)	...	32	11	11	26	7
Chloride (Cl)	40	81	4.1	3.3	6.0	3
Fluoride (F)	...	...	.6[b]	...	...	.4
Nitrate (NO_3)	52	108	.5	.48	Tr.	.0
Free carbon dioxide (CO_2)	...	...	...	...	...	...
Total dissolved solids	273	490	278	319	666	...
Total hardness (as $CaCO_3$)	91	157	41	67	238	69
Analyst[c]	HBR	ATG	ATG	ATG	HBR	EWL
Date of collection	July 2, 1918	July 12, 1918	July 11, 1918	July 12, 1918	May 31, 1918	Sept. 4, 1943

[a] Calculated.
[b] From analyses of sample collected Feb. 13, 1941.
[c] HBR = H. B. Riffenburg, ATG = A. T. Geiger, EWL = E. W. Lohr.

TABLE E.—*Analyses of ground waters from Miocene and Middle Eocene formations—Continued*
(Parts per million)

Well No.	7	8	9	10	11	12
County	Gloucester	Gloucester	Mathews	Mathews	Mathews	King William
Town	Naxera	Gloucester	New Point Comfort	New Point Comfort	Mathews	Cohoke
Depth (feet)	?	40	152	150	?	125
Water-bearing rocks	Yorktown (?)	Yorktown	Yorktown	Yorktown	Calvert (?)	Nanjemoy
Silica (SiO_2)	...	24	...	...	...	...
Iron (Fe)	...	...	...	...	...	...
Calcium (Ca)	...	42	...	...	17	...
Magnesium (Mg)	...	10	...	...	20	...
Sodium (Na), Potassium (K)	...	114[a]	...	...	351[a]	...
Bicarbonate (HCO_3)	485	178	264	268	800	203
Sulfate (SO_4)	100	60	120	120	9.5	6
Chloride (Cl)	65	90	72	103	156	3
Fluoride (F)	.2	...	...	...	...	.4
Nitrate (NO_3)	...	72	...	...	Tr.	.3
Free carbon dioxide (CO_2)	...	...	...	...	...	...
Total dissolved solids	...	548	...	...	1090	...
Total hardness (as $CaCO_3$)	300	146	342	375	124	93
Analyst[b]	MDF	HBR	EWL	EWL	HBR	EWL
Date of collection	Feb. 13, 1941	July 21, 1918	July 22, 1943	Nov., 1943	June 17, 1918	Sept. 2, 1943

[a] Calculated.
[b] MDF = M. D. Foster, HBR = H. B. Riffenburg, EWL = E. W. Lohr.

TABLE E.—*Analyses of ground waters from Miocene and Middle Eocene formations—Continued*
(Parts per million)

Well No.	13	14	15	16	17	18
County	New Kent	James City	York	York	York	York
Town	Providence Forge	Jamestown	Ewell	Camp Peary	Yorktown	Yorktown
Depth (feet)	110	105	265	267	spring	400
Water-bearing rocks	Nanjemoy	Nanjemoy	Calvert	Calvert	Yorktown	Calvert (?)
Silica (SiO_2)	26	...	...	...	...	...
Iron (Fe)	.03	...	...	...	...	...
Calcium (Ca)	33	...	...	...	...	...
Magnesium (Mg)	4.4	...	...	...	...	...
Sodium (Na), Potassium (K)	8.7[a]	...	...	...	...	...
Bicarbonate (HCO_3)	131	265	223	400	221	806
Sulfate (SO_4)	7.0	8	8	1	5	50
Chloride (Cl)	2.9	36	4	22	8	388
Fluoride (F)	.2	1.3	1.0	1.9	.2	2.0
Nitrate (NO_3)	.0	0	...	...	1.8	...
Free carbon dioxide (CO_2)	.7	...	...	...	...	...
Total dissolved solids	144	...	...	...	...	...
Total hardness (as $CaCO_3$)	100	21	26	24	183	24
Analyst[b]	EWL	EWL	EWL	JDB	MDF	MDF&LWM
Date of collection	Dec. 31, 1943	Oct. 6, 1943	Dec. 19, 1942	Dec. 12, 1942	Feb. 7, 1941	Feb. 8, 1941

[a] Calculated.
[b] EWL = E. W. Lohr, JDB = J. D. Boreman, MDF = M. D. Foster, MDF&LWM = M. D. Foster and L. W. Miller.

TABLE E.—*Analyses of ground waters from Miocene and Middle Eocene formations—Continued*
(Parts per million)

Well No.	19	20	21	22	23	24
County	Elizabeth City	Elizabeth City	Northampton	Accomack	Prince George	Nansemond
Town	Big Bethel	Newport News	Kiptopeke	Chincoteague	Newville	Drivers
Depth (feet)	100	138	60	60	38	46
Water-bearing rocks	Yorktown	Yorktown	Yorktown	Yorktown	Yorktown	Yorktown
Silica (SiO_2)	...	42	...	...	...	11
Iron (Fe)	...	19	...	...	1.3	7.7
Calcium (Ca)	...	26	...	...	...	125
Magnesium (Mg)	...	9.0	...	...	...	9.0
Sodium (Na)	...	61	...	...	...	10
Potassium (K)	...	4.3	...	...	...	3.7
Bicarbonate (HCO_3)	242	163	98	12	146	247
Sulfate (SO_4)	8	24	3	3	25	105
Chloride (Cl)	109	54	24	11	4	22
Fluoride (F)	.4	.1	.5	...	.1	0
Nitrate (NO_3)	1.6	.60	.4	...	1.0	38
Free carbon dioxide (CO_2)	...	40	...	...	16	0
Total dissolved solids	...	306	...	...	...	464
Total hardness (as $CaCO_3$)	200	102	84	10	132	349
Analyst[a]	MDF	WMN	EWL		MDF	MDF
Date of collection	Mar. 21, 1942	Aug. 6, 1940	May 6, 1942	June 15, 1944	July 11, 1939	Aug. 1, 1939

[a] MDF = M. D. Foster, WMN = W. M. Noble, EWL = E. W. Lohr.

TABLE E.—*Analyses of ground waters from Miocene and Middle Eocene formations—Continued*
(Parts per million)

Well No.	25	26	27	28[a]	29[b]
County	Norfolk	Norfolk	Princess Anne	Princess Anne	Princess Anne
Town	Norfolk	Great Bridge	Lynnhaven	Dam Neck	Dam Neck
Depth (feet)	135	64	38	164	135
Water-bearing rocks	Yorktown	Yorktown	Yorktown	Yorktown	Yorktown
Silica (SiO_2)	....	27	16	....	....
Iron (Fe)	7.2	.67	5.62	....	....
Calcium (Ca)	....	68	5.4	....	35
Magnesium (Mg)	....	4.9	6.8	....	....
Sodium (Na)	....	41	50	....	....
Potassium (K)	....	2.6	3.5	....	....
Bicarbonate (HCO_3)	160	243	47	280	270
Sulfate (SO_4)	23	5.0	3.1	2	1
Chloride (Cl)	44	54	81	148	290
Fluoride (F)	.3	0.6	....	.1	.2
Nitrate (NO_3)	.85	0	1.0	....	....
Free carbon dioxide (CO_2)	15	2.5	....	....	....
Total dissolved solids	....	325	210	....	692
Total hardness (as $CaCO_3$)	117	190	41	210	188
Analyst[c]	MDF	MDF	MDF	SKL	EWL
Date of collection	Aug. 31, 1939	Aug. 28, 1939	Aug. 30, 1939	Nov. 20, 1942	Oct. 3, 1942

[a] Target Range No. 1.
[b] Rifle Range No. 2.
[c] MDF = M. D. Foster, SKL = S. K. Love, EWL = E. W. Lohr.

undoubtedly due to organic pollution, since the nitrate is also very high, 108 parts per million. Other samples (Table E, 8, 24) containing high nitrate also contain somewhat more chloride than might otherwise be expected. These samples were taken from dug wells. Samples at inland localities taken from drilled wells generally contain very little nitrate or chloride.

Water from the Calvert strata contains somewhat less chloride than water from the Eocene strata. At Camp Peary, water from the Eocene strata contains about 300 parts per million, whereas water from basal Miocene beds contains only about 20 parts of chloride. At Yorktown the difference is less; the Park Service well, which is sunk to Miocene deposits, yields water having about 400 parts of chloride, whereas deeper wells reaching Eocene sands at the Naval Mine Depot yield water containing from 500 to 600 parts per million of chloride. The well[18] at Mathews (Table E, 11) yielding water containing 156 parts of chloride, reported to be a flowing well 817 feet deep, probably obtained water from the Calvert at about 400 feet. (A 650-foot well in this county yields water containing 550 parts of chloride).

Iron is present in large amounts in some waters from Miocene strata. Analyses 20, 24, 25, and 27 of Table E, contain respectively 19, 7.7, 7.2 and 5.62 parts per million of this constituent. A few other samples contain only a little iron, and in the samples recently analyzed iron may be presumed to be practically absent since it was not reported.

The iron present in many samples may have its source in the sediments, but, since some of these waters contain a relatively high free carbon dioxide content, some of the iron may be derived from pipes or tanks through which the water passes. A sample from Newport News (Table E, 20) contained 40 parts of free carbon dioxide. On the other hand, several samples (Table E, 13, 24, 26) contained little or none.

Fluoride is not greater than .6 part per million in water from the Yorktown formation, but water from the older formation contains from 1 to 2 parts.

Taking the waters as a group, it would appear that a very few of the samples of low mineralization may represent waters that are largely of local origin, and their constituents are the result of simple solution of the sediments through which they have moved. These waters are similar to most water obtained from Quaternary deposits. Most of the other samples, however, appear to have traveled farther and have been acted upon by base exchange material in the sediments; in most instances more or less of the calcium bicarbonate, originating from the solution of limy marls by waters high in carbon dioxide, has been converted to sodium bicarbonate. In the deeper waters from the Calvert and Nanjemoy formations the major part of the calcium has been exchanged for sodium. These waters are more like samples taken from underlying Lower Eocene or Cretaceous deposits than from overlying Yorktown strata. Several samples contain moderate to fairly high sulfate, originally present as calcium sulfate. Where small amounts of sulfate are present, the sulfates have been converted to sodium sulfate, but, in three samples containing high sulfate, the sulfate is present as calcium sulfate. These samples also contain chloride as calcium (or magnesium) chloride. Obviously here base exchange has acted to fix sodium and liberate calcium.

USE OF WATER

The water from the Yorktown deposits is admirably suited to irrigation because of its high ratio of calcium to sodium and potassium. In many places, it is satisfactory for domestic purposes in spite of its hardness, but elsewhere the presence of iron is troublesome. The water is used widely for boiler feed, but the continual use of boiler compound is necessary for successful operation. Complete softening and iron removal are practiced where the water is used by commercial laundries. Water from the Calvert and Nanjemoy formations is more suitable for domestic purposes because of its low hardness. In this type of water, as with water from deeper wells, chloride and fluoride may be present in objectionable amounts in many places.

WATER FROM QUATERNARY DEPOSITS

Thousands of shallow wells throughout Tidewater Virginia obtain water from sands of the Columbia group of Pleistocene age. A few wells are developed in recent dune sands in Princess Anne County. The majority of shallow wells are dug, but a number of them are driven or jetted. Nearly all these wells are domestic wells supplying homes and farms. In two places, batteries of shallow wells furnish water to small industries. Seashore State Park, near Cape Henry, is supplied by a battery of wells obtaining water from dune sand.

CHEMICAL CHARACTER

Water from shallow wells, being practically everywhere of local origin, generally contains a low or very low amount of dissolved solids, but a few, particularly those located on the lower easterly marly terraces, contain about as much dissolved mineral matter as the deeper waters from Miocene strata.

Samples 7, 8, 9, and 11 of Table F contain from 300 to 400 parts of total dissolved solids, but most of the other samples appear to contain a considerably smaller amount of dissolved material. The samples from Reedville and Poquoson (Table F, 5, 16), which contain respectively 775 and 814 parts per million total dissolved solids, seem to be exceptional.

Most of the samples contain more sodium and bicarbonate than any other constituent; several have moderate hardness (less than 100 parts per million). The sample from Poquoson (Table F, 16) has high bicarbonate hardness, as well as high chloride. Samples 5, 7, and 16 of Table F contain more than 100 parts of chloride, probably originating as salt spray, and samples 4, 9, 10, 18, 19, and 21 contain a high nitrate, suggesting organic pollution.

In relatively few places, iron is present in troublesome amounts. Free carbon dioxide is probably fairly high in most shallow waters (Table F, 2, 13, 14, and 17) and, since the total mineralization is low, some of these waters are acid and corrosive. Fluoride is very low or absent.

The samples from dune sands (Table F, 14, 15, 16) are of the same character as the slightly mineralized waters from the terrace sands.

TABLE F.—*Analyses of ground waters from Quaternary formations*
(Parts per million)

Well No.	1	2	3	4	5
County	Westmoreland	Westmoreland	Northumberland	Northumberland	Northumberland
Town	Washington's Birthplace	Stratford	Lewisetta	Coan	Reedville
Depth (feet)	Spring	Spring	22	27	14
Silica (SiO_2)	...	8.7	15	12	43
Iron (Fe)	...	.02	.02	.23	...
Calcium (Ca)	...	1.8	20	2.6	18
Magnesium (Mg)	...	1.5	7.8	7.1	11
Sodium (Na)	...	2.4	53	45	256
Potassium (K)	...	1.1			
Bicarbonate (HCO_3)	110	5.0	80	75	95
Sulfate (SO_4)	15	2.6	45	3.5	31
Chloride (Cl)	4	3.9	54	28	380
Fluoride (F)	.2	...	...	...	...
Nitrate (NO_3)	8.4	5.0	2.9	21	Tr.
Free carbon dioxide (CO_2)	...	37	...	...	...
Total dissolved solids	...	32	254	156	775
Total hardness (as $CaCO_3$)	105	11	82	36	90
Analyst[a]	EWL	EWL	ATG	ATG	HBR
Date of collection	Sept., 1944	Aug. 27, 1935	July 5, 1918	July 2, 1918	July 1, 1918

[a] EWL = E. W. Lohr, ATG = A. T. Geiger, HBR = H. B. Riffenburg.

TABLE F.—*Analyses of ground waters from Quaternary formations—Continued*
(Parts per million)

Well No.	6	7	8	9	10
County	Northumberland	Richmond	Gloucester	Gloucester	Essex
Town	Reedville	Farnham	Pampa	Dutton	Caret
Depth (feet)	18	44	23	23	30
Silica (SiO_2)	34	....	....	58	....
Iron (Fe)	2.9	....	....	.12	....
Calcium (Ca)	4.0	1.2	5.2	11	4.0
Magnesium (Mg)	2.2	1.0	1.0	11	20
Sodium (Na) Potassium (K)	49	110	100	64	26
Bicarbonate (HCO_3)	55	117	152	135	12
Sulfate (SO_4)	13	7.1	8.2	18	Tr.
Chloride (Cl)	42	100	64	38	60
Fluoride (F)	....	....	....	....	....
Nitrate (NO_3)	Tr.	2.0	14	35	68
Free carbon dioxide (CO_2)	....	....	....	....	....
Total dissolved solids	171	315	400	337	247
Total hardness (as $CaCO_3$)	19	7	17	73	92
Analyst[a]	ATG	HBR	HBR	HBR	HBR
Date of collection	July 1, 1918	July 9, 1918	June 5, 1918	June 5, 1918	July 20, 1918

[a] ATG = A. T. Geiger, HBR = H. B. Riffenburg.

Table F.—Analyses of ground waters from Quaternary formations—Continued
(Parts per million)

Well No.	11	12	13	14	15	16
County	Middlesex	King and Queen	Hanover	New Kent	Charles City	York
Town	Urbanna	near Walkerton	Hanover	Providence Forge	Holdcroft	Poquoson
Depth (feet)	28	Spring	Spring	16	40	30
Silica (SiO_2)	...	...	...	...	...	18
Iron (Fe)	...	...	...	...	41	.43
Calcium (Ca)	24	...	...	...	...	180
Magnesium (Mg)	5.7	...	...	...	...	16
Sodium (Na)	83	...	...	...	...	117
Potassium (K)						1.4
Bicarbonate (HCO_3)	81	5	13	18	31	453
Sulfate (SO_4)	15	5	15	28	1	115
Chloride (Cl)	128	3	6	29	19	193
Fluoride (F)	...	.0	.0	.0	.1	.1
Nitrate (NO_3)	2.0	1.2	15	18	.0	.1
Free carbon dioxide (CO_2)	...	...	19	33	...	...
Total dissolved solids	324	...	...	...	...	814
Total hardness (as $CaCO_3$)	83	14	42	62	33	516
Analyst[a]	HBR	EWL	EWL	EWL	EWL	WMN
Date of collection	June 4, 1918	Oct. 1, 1943	Dec. 30, 1943	Dec. 29, 1943	Oct. 6, 1943	Aug. 8, 1940

[a] HBR = H. B. Riffenburg, EWL = E. W. Lohr, WMN = W. M. Noble.

TABLE F.—*Analyses of ground waters from Quaternary formations—Continued*
(Parts per million)

Well No.	17	18	19	20	21	22
County	Prince George	Southampton	Isle of Wight	Princess Anne	Princess Anne	Princess Anne
Town	Disputanta	Franklin	Smithfield	Seashore Park	Kempsville	Dam Neck
Depth (feet)	25	15	12	15	15	10
Silica (SiO_2)	....	....	....	11	....	....
Iron (Fe)	....	8.3	....	3.66	....	1.8
Calcium (Ca)	....	....	....	2.9	....	....
Magnesium (Mg)	....	....	....	2.1	....	....
Sodium (Na)	....	....	....	11	....	....
Potassium (K)	....	....	....	1.2	....	....
Bicarbonate (HCO_3)	6.0	0	48	5.0	5	35
Sulfate (SO_4)	1	23	15	5.1	34	9
Chloride (Cl)	21	18	4.0	21	18	24
Fluoride (F)	.4	.10	.2	.5	.4	.5
Nitrate (NO_3)	.77	75	27	.2	20	1.7
Free carbon dioxide (CO_2)	49	....	....	45	57	....
Total dissolved solids	....	....	....	63	....	....
Total hardness (as $CaCO_3$)	15	76	70	16	50	27
Analyst[a]	MDF	WMN	WMN	MDF	MDF	MDF
Date of collection	July 10, 1939	Dec. 13, 1937	Dec. 4, 1937	Aug. 30, 1939	Aug. 28, 1939	Aug. 24, 1939

[a] MDF = M. D. Foster, WMN = W. M. Noble.

REFERENCES

1. Cady, R. C., Ground-water resources of northern Virginia: Virginia Geol. Survey Bull. 50, p. 127, 1938.

2. Campbell, M. R., Alluvial fan of Potomac River: Geol. Soc. America Bull., vol. 42, no. 3, pp. 825-853, 1931.

3. Cederstrom, D. J., Chloride in ground water in the Coastal Plain of Virginia: Virginia Geol. Survey Bull. 58, 1943.

4. ———— Structural geology of southeastern Virginia: Am. Assoc. Petroleum Geologists Bull., vol. 29, no. 1, pp. 71-95, 1945.

5. ———— Selected logs of wells in the Virginia Coastal Plain north of James River: Virginia Geol. Survey Circular 3, 1945.

6. ———— Geology and ground-water resources of the southeastern Virginia Coasal Plain: Virginia Geol. Survey Bull. 63, 1945.

7. ———— Genesis of ground waters in the Coastal Plain of Virginia: Econ. Geology, vol. 41, no. 3, pp. 218-245, 1946.

8. Clark, W. B., Miller, B. L., The physiography and geology of the Coastal Plain province of Virginia: Virginia Geol. Survey Bull. 4, p. 6, 1912.

9. Cushman, J. A., Foraminifera from the Aquia formation of Virginia: Contr. Cushman Lab. Foraminiferal Research, vol. 20, no. 11, pp. 17-28, 1944.

9a. Cushman, J. A., and Cederstrom, D. J., An Upper Eocene foraminiferal fauna from deep wells in York County, Virginia: Virginia Geol. Survey Bull. 67, 1945.

10. Darton, N. H., U. S. Geol. Survey, Geol. Atlas, Norfolk folio (no. 80), pp. 1-2, 1902.

11. Dean, H. T., Chronic endemic dental fluorosis (mottled enamel): Jour. Am. Med. Assoc., vol. 107, no. 16, pp. 1269-1272, 1936.

12. ———— Fluorine and dental health: Am. Assoc. Adv. Sci. Bull., vol. 1, no. 6, p. 47, 1942.

13. Ewing, W. M., Crary, A. B., Rutherford, H. M., and Miller, Benjamin, Geophysical investigations in the emerged and submerged Atlantic Coastal Plain: Geol. Soc. America Bull., vol. 48, no. 6, pp. 753-812, 1937.

14. Renick, B. C., Geology and ground-water resources of central and southern Rosebud County, Montana: U. S. Geol. Survey Water-Supply Paper 600, 1929.

15. Richards, H. G., Subsurface stratigraphy of Atlantic Coastal Plain between New Jersey and Georgia: Am. Assoc. Petroleum Geologists Bull., vol. 29, no. 7, p. 907, 1945.

16. Riffenburg, H. B., The chemical character of ground water in the Coastal Plain of Virginia: U. S. Geol. Survey, unpublished manuscript, 1918.

17. Ross, C. S., Clays and soils in relation to geologic processes: Wash. Acad. Sci. Jour., vol. 33, no. 8, pp. 225-235, 1943.

18. Sanford, S. T., Underground water resources of the Coastal Plain province of Virginia: Virginia Geol. Survey Bull. 5, 1912.

19. Schachtschabel, F., Research on the sorption of clay minerals and organic colloids and the estimation of the fraction of these colloids in the sorption in soils: Kolloid Beihefte, Band 51, pp. 199-276, 1940.

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